# Riparian buffer strips and their effectiveness as a natural flood management measure

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# Abstract

Riparian buffer strips are an established land management measure utilised to address diffuse pollution from agriculture and improve ecology. Previous studies have emphasised the multiple benefits of riparian buffer strips such as nutrient filtration and sediment trapping, which can be transported in overland flow and implies runoff is attenuated. Riparian buffer strips are not explicitly considered a natural flood management (NFM) measure. Nonetheless, they have the potential for inclusion to the catalogue of nature-based measures being implemented to reduce runoff and flood risk, while offering multiple benefits. An ecosystem services (ES) approach can be adopted to assess NFM multiple benefits (as *multiple* ES) and this study utilises a subset of ES to provide an example of this. Regulating and supporting ES were utilised to determine the effectiveness of riparian buffer strips as an NFM measure. At field scale, an experimental approach assessed flood regulation by monitoring runoff attenuation in a riparian buffer strip situated on an agricultural hillslope. An indication of nutrient cycling and primary production conditions at field scale was achieved by monitoring algae biomass and comparing a buffered and non-buffered site. The interaction between precipitation events, land management changes and nutrient concentrations were considered at the buffered site in relation to runoff attenuation and algae biomass response. At catchment scale, the Soil and Water Assessment Tool was utilised to explore reduction in peak flow (flood regulation) in response to varying scenarios of catchment-wide riparian buffer strips in terms of width and vegetation type.

The empirical field observations demonstrated the riparian buffer strip provided runoff attenuation. Higher volumes of runoff coincided with bare soils in the adjacent field, wetter antecedent conditions, higher precipitation depths and intense precipitation. However, runoff attenuation could be improved. On the hillslope, microtopography of vehicle tracks diverted overland flow away from the buffer but the field corner demonstrated potential for a complimentary runoff attenuation feature (e.g. a temporary storage pond). At catchment scale, the 10 m grass-based buffer strip was concluded to be most effective for flood regulation and achieve a greater ratio of peak flow reduction (average 7.2%) to area of land required (2.1% of catchment). The riparian buffer strip demonstrated marginally better ecological quality conditions for nutrient cycling and primary production compared to the non-buffered site. Buffer shading positively affected the supporting ES. The study suggested high flows as a likely dominant influence on algae biomass. Overall, riparian buffer strips were concluded to be an effective NFM measure at field and catchment scale but could be improved with complimentary measures when located on a hillslope.

**‘Whāia te iti kahurangi ki te tūohu koe me he maunga teitei’**

*Seek the treasure you value most dearly: if you bow your head, let it be to a lofty mountain*

Maori Whakataukī (proverb) about aiming high, being persistent and not allowing anything to stop you reaching your goal

*Thank you Mum*

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# Abbreviations

| | |
|---|---|
| %↓Qpk | Percentage reduction in peak discharge |
| AAR | Annual average rainfall |
| AECS | Agri-environment climate scheme |
| ALPHA_BF | Baseflow alpha factor |
| AMAX | Annual maximum |
| API | Antecedent Precipitation Index |
| BS | British Standard |
| CEDA | Centre for Environmental Data Analysis |
| CEH | Centre for Ecology and Hydrology |
| CFSR | Climate Forecast System Reanalysis |
| Chl-a | Chlorophyll *a* |
| CSE | Catchment Systems Engineering |
| CULT | Cultivated |
| Daisy | Danish Simulation Model |
| DOC | Dissolved Organic Carbon |
| DRAINMOD | A hydrology model |
| DTM | Digital Terrain Model |
| EPCO | Plant uptake compensation factor |
| EPIC | Environmental Policy Integrated Climate Model |
| ESCO | Soil evaporation compensation factor |
| EU | European Union |
| FEH | Flood estimation handbook |
| GAEC | Good agricultural and environmental conditions |
| GEV | Generalised Extreme Value distribution |
| GIS | Geographic Information System |
| GL | Generalised Logistic distribution |
| GW_DELAY | Threshold depth of water in the shallow aquifer required for return flow to occur |
| GWQMN | Threshold depth of water in the shallow aquifer required for return flow to occur |
| HOST | Hydrology of Soil Types |
| HRU | Hydrological response unit |
| HSPF | Hydrological Simulation Program - FORTRAN |
| HYDGRP | Hydrological group |
| HYDRUS | A Windows-based modelling software |
| IDC | SWAT land cover/plant descriptions |
| INRIP | Inside riparian buffer strip |
| IPCC | Intergovernmental Panel on Climate Change |
| KINEROS | Kinematic Runoff and Erosion model |
| LAI | Leaf Area Index |
| LCM | Land Cover Map |
| LiDAR | Light Detection and Ranging |
| LMOM | L-Moments |
| mAOD | Metres above ordnance datum |

| | |
|---|---|
| MEA | Millennium Ecosystem Assessment |
| MIDAS | Met Office Integrated Data Archive System |
| MIKE-SHE | An integrated hydrological modelling system for building and simulating surface water flow and groundwater flow |
| MIT | Minimum inter-event time |
| MODFLOW | Modular finite-difference model |
| MT3DMS | Modular Three-Dimensional Transport Model |
| NBS | Nature based solution |
| $NH_4$-N | Ammonium |
| $NO_3$-N | Nitrate |
| NS | Nash-Sutcliffe Efficiency |
| OAT | One-at-a-time |
| OUTRIP | Outer riparian buffer strip at field edge |
| OV_N | Manning's 'n; value for overland flow |
| PCP | Precipitation |
| PDF | Probability distribution function |
| $PO_4$-P | Phosphate |
| PPU | Latin hypercube 95% probability distribution |
| PVA | Potentially Vulnerable Area |
| QMED | Median of annual maximum |
| Qpk | Peak flow |
| RAFs | Runoff attenuation features |
| REVAPMN | Threshold depth of water in the shallow aquifer for 'revap' to occur |
| RQ | Research question |
| RZWQM | Root Zone Water Quality Model |
| SCS | Soil conservation service |
| SEMI | Semi natural |
| SEPA | Scottish Environment Protection Agency |
| SFPS | Single Farm Payment Scheme |
| SMR | Statutory management requirements |
| SOL_AWC | Available water capacity of all soil layers |
| SOL_K | Saturated hydraulic conductivity |
| SPA | Service provisioning areas |
| SPR | Standard Percentage Runoff |
| SRDP | Scottish Rural Development Programme |
| SRUC | Scottish Rural University College |
| SS | Suspended sediment |
| SUFI-2 | Sequential Uncertainty Fitting |
| SWAT | Soil and Water Assessment Tool |
| SWAT-CUP | SWAT calibration and uncertainty procedures |
| SWAT-REMM | Riparian Ecosystem Management Model |
| TOPMODEL | TOPography based hydrological MODEL |
| Total-N | Total nitrogen |
| Total-P | Total phosphorus |
| TOUGH2 | Transport of Unsaturated Groundwater and Heat model |

| | |
|---|---|
| Ttp | Time to peak |
| UKCP | UK Climate Projections |
| UKNEA | United Kingdom National Ecosystem Assessment |
| UKTAG | United Kingdom Technical Advisory Group |
| VFS | Vegetated Filter Strip |
| VWC | Volumetric water content |
| WARMF | Watershed Analysis Risk Management Framework |
| WEPP | Water Erosion Prediction Project model |
| WFD | Water Framework Directive |
| WWNP | Working with natural processes |

# Chapter 1 Introduction

## 1.1 Background

Flooding is a global concern and predicted to occur more often and with greater severity in the future. Increasing flood risk is driven by a multitude of factors including climate change, population growth (and in turn, food demand), urbanisation, land use and land management changes. Scotland is at increasing risk from flooding as it has experienced a 17% increase in extremely wet days with intense rainfall since 1961 (Met office, 2019). Extreme flood events have been prevalent in the UK in recent years. The winter flooding of 2015-2016 for example, was widespread across the UK; particularly devastating impacts were experienced in the River Dee catchment in Scotland. Research predicts climate change to drive wetter autumnal and winter weather; and drier summers with more intense convective rainfall events in the UK (IPCC, 2014). Intense rainfall coupled with increased impermeable surfaces from urbanisation and more intense land management practices (particularly in agriculture) is likely to exacerbate runoff generation and thereby flood risk.

Continuation of the reliance on traditional hard engineered approaches to flood risk management (FRM) is costly and unsustainable (SEPA, 2016a). There is a growing interest in working with natural processes (WWNP) to provide nature-based solutions to flood risk; referred to as natural flood management (NFM) in Scotland. The concept of NFM is to utilise the abilities of the landscape's natural processes and features to slow, intercept and store water, as well as provide multiple benefits. NFM measures include woodland planting, storage ponds, floodplain reconnection, and land management practices which provide FRM services while offering multiple benefits.

It is widely accepted that agricultural land management intensification creates greater hydrological connectivity, increases surface runoff to river systems (Lane et al., 2003) and has potential to contribute to downstream flooding (O'Connell et al., 2007; Wheater and Evans, 2009; Wilkinson et al., 2014). As described by Lane (2003), it is vital to control these overland hydrological pathways by means of interception and storage, as well as improve land management practices. The steep topographical characteristics of catchment uplands and surrounding agricultural land are prime sources of runoff and therefore effective areas to target runoff source control and implement NFM measures.

Riparian buffer strips are an established land management measure to address diffuse pollution from agriculture and to improve/provide ecological habitats. Despite the water quality origins of riparian buffer strips, their fundamental function is to intercept nutrients and sediments transported by surface runoff. This interception and attenuation of surface runoff are properties of NFM measures, yet a significant research gap exists in relation to the effectiveness of riparian buffer strips as an NFM measure (De Sosa et al., 2018b; Environment Agency, 2017a). There are substantial studies on riparian buffer strips based on a single function and related to water quality

(Stutter et al., 2012). Studies also emphasise the individual multiple benefits in isolation provided by riparian buffer strips, which is a further quality of NFM measures. Surface runoff pathways transport nutrients, sediments and pollutants but studies rarely quantify the runoff volumes as they are more concerned with concentrations of diffuse pollutants. There is a lack of data on the effect of riparian buffer strips on surface runoff at hillslope and catchment scales (Environment Agency, 2017a). This thesis contributes to addressing this gap in knowledge through empirical monitoring of surface runoff entering a riparian buffer strip on a hillslope and hydrological modelling at catchment scale. Hydrological models are commonly adopted to predict how changes in land management affects peak flows at larger landscape scales (Beven, 2012). The field scale aspect of this study provides on-the-ground observations, but it is challenging to extrapolate the behaviours of a field study to catchment scale due to uncertainty in the applicability of localised conditions to larger spatial scales. A hydrological modelling approach is therefore applied in this thesis to estimate the impact of catchment-wide riparian buffer strips on reducing and delaying the flood peak at larger landscape scales.

A key criterion of NFM measures is that they provide multiple benefits. An approach to examining these multiple benefits is to use an ecosystem services (ES) approach, which is a concept proposed by Daly (1997) and Costanza et al. (1997) and gathered precedence following the publication of the Millennium Ecosystem Assessment (MEA) (2003). The consideration of economic and societal dependences on ecological systems was the premise of the ES concept (Costanza et al., 2017). Although this thesis is based on understanding flood management capability of riparian buffer strips, a subset of ES are used as an example of how the ES approach could be applied to assess NFM multiple benefits.

The MEA classified ES into *supporting*, *regulating*, *provisioning* and *cultural* categories, and have remained the dominant classification utilised in research. Developments and advocation of utilising the ES approach to understand NFM multiple benefits are becoming more popular (Collentine and Futter, 2018; Frontier Economics Ltd et al., 2013; Iacob et al., 2012; Keesstra et al., 2018) but a unified method to incorporate ES into decision making is lacking (Böck et al., 2018; Costanza et al., 2017; Grizzetti et al., 2016). Dittrich et al. (2018) also recognise the absence of studies which assess the benefits of NFM measures in relation to ES. Contributing to this research gap is the scarcity of NFM research quantifying the impact of measures on flood risk, as well as their multiple benefits (Dadson et al., 2017; De Sosa et al., 2018b). Quantification and evidence of the multiple benefits of an NFM measure provide meaningful justification for associated costs of implementation for funding and hence, is important to improve uptake of measures. NFM multiple benefits can be translated as multiple ES (Gilvear et al., 2013) as the premise of the ES concept is to consider dependencies on ecological systems (Costanza et al., 2017) and thereby consider when these multiple ES improve or degrade.

In this study, flood mitigation is considered a regulating ES (flood regulation) and assessed alongside supporting ES of nutrient cycling and primary production. These supporting ES crucially underpin other ES providing an understanding of potential impact or feedbacks on multiple ES. Algae biomass have an integral role in nutrient cycling and primary production, which fundamentally underpin multiple ES. Hence algae biomass is used as an indicator of these supporting ES.

A framework outlining the ES approach to this study is illustrated in Figure 1.1 demonstrating how flood regulation will be assessed at field (Site A, Figure 1.1) and catchment scale whereas, nutrient cycling and primary production will be examined at field scale (Site A and B, Figure 1.1). This thesis aims to address a research gap in quantifying and understanding multiple ES in relation to the effectiveness of riparian buffer strips as a valid NFM measure when located on a hillslope (using a field-scale experiment) and when implemented at catchment scale (using modelling). At field scale, assessment of flood regulation and supporting ES is accomplished by assessing the interaction of riparian buffer strips with land management, surface runoff, (weather) event conditions and algae biomass. At catchment scale, flood regulation is examined using hydrological modelling of catchment-wide riparian buffer strips of varying widths and vegetation type.

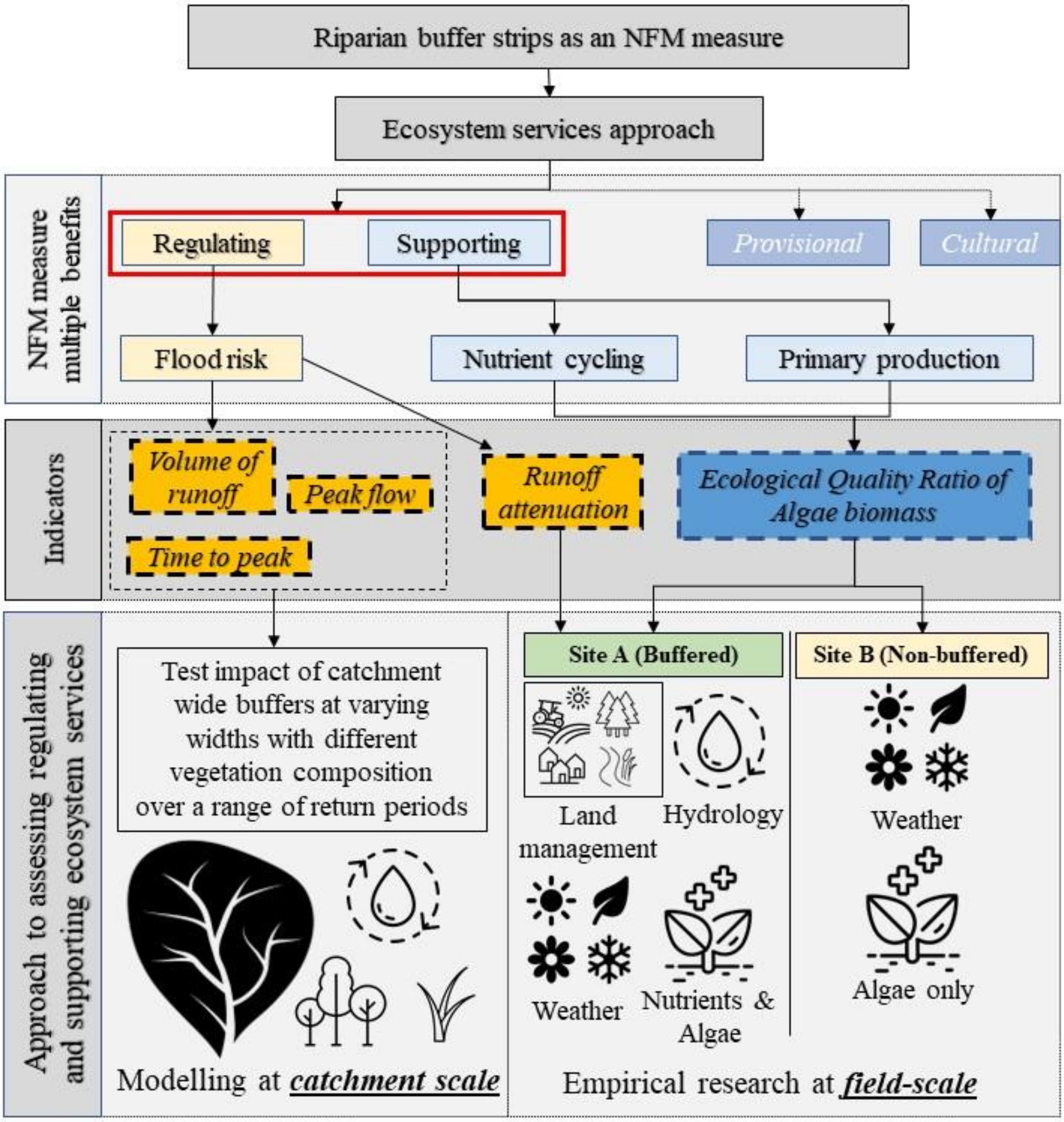



Figure 1.1 Framework of the ES approach adopted for this study and how each element of the study will be assessed (indicators) and the method for the assessment at catchment and field scale. Red box highlights the focus of this study on regulating and supporting ecosystem services. Dashed boxes identify indicators. Graphics courtesy of the noun project.

## 1.2 Research aim

The aim of this thesis is to establish whether riparian buffer strips can be considered an effective NFM measure by providing multiple ES including (regulating ecosystem service) flood regulation at field and catchment scale and (supporting ecosystem services) nutrient cycling and primary production at field scale.

### *1.2.1 Research questions*

The following research questions (RQ) are addressed by this thesis:

***RQ1: What are the different conditions by which overland flow moves into and through riparian buffer strips?***

- Do riparian buffer strips demonstrate natural flood management merits of runoff attenuation at field scale when located on a hillslope with rotational arable land management in the adjacent field?
- Does land management practices or event conditions affect the volume of overland flow entering the riparian buffer strip?
- Does land management practices or event conditions influence the ability of riparian buffer strips to receive overland flow and attenuate surface runoff?

***RQ2: What is the impact of riparian buffer strips on algae biomass in streams as an indicator of nutrient cycling and primary production?***

- Is there a difference in algae biomass ecological quality ratio between a riparian buffer strip site and a non-buffered site?
- How do event conditions affect algae conditions at a riparian buffer strip site and a non-buffered site?
- Are there any trends in algae concentrations following land management changes at the riparian buffer strip site?

***RQ3: How effective are riparian buffer strips implemented at catchment scale at reducing peak flow and what is the most effective riparian buffer strip width and vegetation type (using SWAT model as a tool)?***

- What width of catchment-wide riparian buffer strip reduces peak flow ($m^3/s$) is most effective at upper, middle and lower catchment scale?
- Do grass-based or tree-based riparian buffer strips provide a greater reduction in peak flow?

## 1.3 Layout of thesis

| | |
|---|---|
| ***Chapter 2 Literature review*** | Outlines relevant literature to this study. An overview of NFM and riparian buffer strips is provided, highlighting previous research indicating their applicability as an NFM measure. Agricultural land use management practices and their influence on runoff generation is summarised. Hydrological modelling is described and focuses on two models considered for this study, later focusing on SWAT and its mechanisms for replicating catchment-wide riparian buffer strips. Multiple benefits of riparian buffer strips (and more specifically algae) are outlined in the context of ecosystem services. |
| ***Chapter 3 Experimental methodology*** | The methods utilised to address RQ1 and RQ2 are outlined in this chapter. The case study catchment is introduced followed by the experimental design, implementation and subsequent analysis methods for RQ1. This is repeated for methods adopted for RQ2 and the chapter is then summarised. |
| ***Chapter 4 Modelling methodology*** | The hydrological modelling methods used to answer RQ3 are described. An introduction to SWAT and the model setup process is followed by the approach to calibration and validation using SWAT-CUP software. The scenarios tested to answer RQ3 are outlined with a subsequent outline of analysis methods and uncertainties to be considered. |
| ***Chapter 5 Experimental results*** | The results pertaining to RQ1 and RQ2 are presented. |
| ***Chapter 6 Modelling results*** | The results pertaining to RQ3 are presented. |
| ***Chapter 7 Discussion*** | Discusses the results of the research and links the three RQs to establish the effectiveness of riparian buffer strips as an NFM measure. |
| ***Chapter 8 Conclusion*** | Provides conclusion of this research and proposes future research. |

# Chapter 2 Literature review

## 2.1 Climate change and flood risk in the UK

The natural phenomenon of flooding is becoming a greater risk as climate change amplifies heavy precipitation events. The Intergovernmental Panel on Climate Change (IPCC) have identified a likely increase in flooding across Northern Europe from climate change with rising temperatures fuelling more frequent intensive precipitation events (IPCC, 2014). Climate change will likely affect the hydrology of river basins with an expected increase in autumnal and winter rainfall, thereby elevating peak discharges (IPCC, 2014). The recent UK Climate Projections (UKCP18) will further the understanding of the global IPCC (2014) predications on a regional UK scale and, more specifically, identify regions likely to receive these intense precipitation events. UKCP18 (Met office, 2019) estimate an increase of 17% in rainfall from extremely wet days between 2008-2017 (defined as exceeding the 99$^{th}$ percentile of baseline 1961-1990 rainfall) and the greatest changes occurring in Scotland. The trend of increased rainfall and inherent risk of flooding in Scotland is clear.

Over recent decades the cost of flooding worldwide has become significant. In Europe, annual flood damages are estimated at €5.3 billion, predicted to increase to €40 billion by 2050 (Alfieri et al., 2015). Recent floods in the UK during winter 2015-16 cost insurers £1.3 billion (Association of British Insurers, 2016) and required emergency government funding of £200 million (Priestley, 2016). More frequent extreme flood events are likely to increase the damage costs, as well as become increasingly burdensome on society, the economy and environment.

FRM is thereby at the forefront of many agendas. Traditionally, FRM adopted structural hard-engineered solutions such as flood walls or levees. However, European (EU) and UK policy has initiated a paradigm shift in how flood risk is managed by incorporating sustainable solutions and a holistic catchment-based approach. The 2007 EU Directive on the Assessment of Management of Flood Risk (2007/60/EC) (Floods Directive) is a fundamental EU policy which has been transposed into Scottish legislation in the form of the Flood Risk Management (Scotland) Act 2009 (FRM Act). The Floods Directive and FRM Act advocate a sustainable approach to managing flooding; facilitating the emergence of using, or restoring, natural processes or features in the landscape to reduce flood risk; providing multiple benefits and cost effectiveness (SEPA, 2016a). This approach is termed *natural flood management* (NFM) in Scotland (SEPA, 2016a). Alternatives include: *working with natural processes* (WWNP) (Environment Agency, 2017b), *nature based solutions* (NBS) in Europe (IUCN, 2016), *nature based engineering* or *engineering with nature* in North America (Nesshöver et al., 2017), or *catchment systems engineering* (CSE) (Quinn et al., 2010). These concepts, with varying degrees, endorse the use of natural processes or features to manage runoff and flood risk (NFM, WWNP, CSE), address societal changes and climate change mitigation or adaptation (NBS). For the purposes of this study the term NFM will be utilised.

### *2.1.1 Natural flood management*

NFM is a crucial element of sustainable FRM whereby natural processes and features are considered for FRM. NFM includes a plethora of measures aimed at slowing and intercepting overland flow pathways, providing storage and attenuation, improving infiltration and having multiple benefits (Scottish Government, 2011). There are a range of NFM measures utilised in the UK context under broad groups of measure types shown in Table 2.1. Measures vary in the location and the scale at which they can be implemented; as well as the degree of evidence base. There is particularly a lack of research which quantifies NFM multiple benefits as well as impact on flood risk (Environment Agency, 2017a). Riparian buffer strips are not part of the list in Table 2.1, however they are considered as an element of land management in a recent review of NFM evidence (Environment Agency, 2017a).

Table 2.1. Types of natural flood management measures utilised in the UK (Environment Agency, 2017b; SEPA, 2016a)

| ***River and floodplain management*** | ***Land management*** | ***Woodland management*** |
|---|---|---|
| Bank restoration | Land and soil management practices | Catchment woodland |
| Floodplain restoration | Agricultural and upland drainage modifications | Floodplain woodlands |
| In-stream structures (Large woody debris/ leaky dams) | Non-floodplain wetlands | Riparian woodlands |
| Washlands and offline storage ponds | Overland sediment traps | Cross-slope woodland |
| River remeandering | Moorland grip blocking | |
| Wetland restoration | Gully blocking | |
| | Runoff attenuation features (RAFs) | |

**Scales of effectiveness of NFM**

The spatial scale in which NFM measures are implemented will influence their effectiveness. For example, model outputs from Lane and Milledge (2013) demonstrated the impact of a single isolated measure will likely be localised and negligible at larger spatial scales. Even at local scale, the measure may only be effective for lower return periods. However, Quinn *et al.* (2013) demonstrate experimentally the implementation of multiple runoff attenuation features (RAFs) across the Belford catchment had a collective impact downstream. A further model based study by Dixon et al. (2016) recognised that understanding how NFM measures impact time to peak is an important element in providing evidence however is highly uncertain at larger catchment scales as sub-catchment flows can become synchronised. Slowing the time to peak in one tributary may inadvertently synchronise its peak with another in the receiving water course, which exacerbates downstream flood risk (Blanc et al., 2012; Hankin et al., 2017). Lane and Milledge (2013) indicates sub-catchment interventions were not translating to catchment scale; Pattison et al. (2008) and Pattison et al. (2014) discuss these sub-catchment attenuations being negligible at catchment scale, or even enhanced due to peak synchronisation. Impacts at catchment scale are substantially uncertain and depend on spatial and temporal scales (Pattison and Lane, 2012).

Temporal scale of effectiveness is also a fundamental consideration for NFM. Where hard engineered solutions provide immediate protection, NFM often requires time for vegetation to establish and provide benefits (Environment Agency, 2017a). The impact of tree planting on peak flow reduction for example, is variable as they grow, which makes it more challenging to provide evidence of their influence (Stratford et al., 2017). Modelling to provide predictions of their impact is often the most cost and time effective means to obtain estimations (Stratford et al., 2017). However, modelling requires sufficient data to calibrate and increase confidence in the model outputs.

The size of flood event in which NFM measures are effective is also contentious. In general, NFM measures are hitherto shown to be more effective at lower return periods (Dadson et al., 2017; Environment Agency, 2017a; Wilkinson et al., 2013; Williams et al., 2012). NFM effectiveness is debated extensively in relation to different spatial and temporal scales. NFM studies generally depict that the measures are effective at field and local scales for small to medium sized flood events whereas; larger scale studies suggest NFM effectiveness at larger spatial scales are inconclusive and become difficult to quantify (Beven et al., 2008; Blanc et al., 2012; Iacob et al., 2012; Jackson et al., 2008; McIntyre et al., 2012; McIntyre and Marshall, 2010; O'Connell et al., 2007, 2004; Parrott et al., 2009). There is a research gap in understanding the spatial and temporal scales of effectiveness at various return periods in both empirical and modelled studies (Environment Agency, 2017c).

## 2.2 Riparian buffer strips as a natural flood management measure

Riparian buffer strips are linear uncultivated strips of vegetated land adjacent to watercourses (Pert et al., 2010; Stockan et al., 2012). These vegetated zones are typically situated in agricultural landscapes and have traditionally been implemented to mitigate diffuse pollution by trapping sediment and filtering nutrients (Blackwell et al., 2018, 2009; Haddaway et al., 2018; Stutter et al., 2012). Riparian buffer strips are not explicitly considered an NFM measure. In the UK, riparian buffer strips have more recently become a consideration for NFM potential (Environment Agency, 2017a). Previously, only riparian woodlands and in-channel riparian vegetation were regarded as NFM by the Environment Agency (EA) (2014a) and the Scottish Environment Protection Agency (SEPA) (SEPA, 2016a). The EA for example, published their channel management handbook (Environment Agency, 2015) in conjunction with their report on using WWNP to reduce flood risk (Environment Agency, 2014a), which considered riparian vegetation to be within the channel, or riparian zones to be planted with woodland. The Scottish NFM handbook (SEPA, 2016a) recognised riparian woodland as an NFM measure but again does not account for riparian zones consisting of shrubs and grasses. A recent study in Australia by Croke, Thomson and Fryirs (2017) proposed riparian buffer strips should be prioritised within channel banks in upper reaches whereas; out of channel riparian buffer strips are most effective on floodplains. The study highlighted the lack of understanding about the role of riparian buffer strips in mitigating flooding.

Understanding of riparian buffer strips in relation to FRM is limited in literature as hydrological processes are often part of research which is more biased towards other topics (e.g. sediment attenuation or nutrient retention) (Borin et al., 2010; Environment Agency, 2017a; Stutter et al., 2012). Concluded by Lane et al. (2007) and summarised by EA (Environment Agency, 2017a), evidence of the ability of a buffer strips to attenuate runoff remains limited. This is concurred by de Sosa et al. (2018b) in a recent review of riparian research in the UK. This study aims to contribute to this knowledge gap.

There are several other reasons why riparian buffer strips should be explored as an NFM measure:

- Buffer strips have been engrained in environmental policy and best management practices in the capacity of mitigating diffuse pollution for a long period (Collins et al., 2009; Muscutt et al., 1993; Phillips et al., 2000; Scottish Government, 2015; Stutter et al., 2012). Although the distinct widths and vegetation types differ per country or region, buffer strips are widely accepted in the political agenda for improving water quality.
- Riparian buffer strips are widely adopted and accepted by landowners and have been implemented for several years throughout the Scottish Rural Development Programme (SRDP) cycles. Yet there are barriers to NFM implementation and if riparian buffer strips are shown to be an effective NFM measure, these barriers could be counteracted. Studies by McLean et al. (2015), Spray et al. (2015) and Waylen et al. (2018) demonstrate the barriers to implementing NFM measures including:
    - Funding for NFM measure implementation, ongoing maintenance and the loss of agricultural productive land;
    - Uncertainty in NFM capabilities (e.g. scales of effectiveness as outlined in Section 2.1.1);
    - New skills and expertise required for NFM implementation and maintenance; and
    - Not being compatible with rural business strategies (e.g. subsidies to locate NFM measures in highly productive agricultural land are inadequate).
- An extensive evidence base exists which quantifies the multiple benefits (explored in more detail in Section 2.2.4) of riparian buffer strips could be complimented by further studies focused on hydrology. Vidon and Hill (2006) recommend improving

understanding of hydrological processes in riparian buffers will enhance understanding of pollution fate (De Sosa et al., 2018b).

As previously stated, riparian buffer strips are often assessed as extensive woodland or on the floodplain, yet riparian buffer strips are implemented across a range of topography. The focus of the empirical element of this research is of hillslope riparian buffer strips. The fundamental criteria of an NFM measure is for it to slow runoff and intercept overland flow pathways and/or provide attenuation (storage), as well have multiple benefits (Parliamentary Office of Science and Technology, 2011). This study aims to ascertain whether agricultural surface runoff is attenuated by a riparian buffer strip on a hillslope and simultaneously assess multiple benefits.

### *2.2.1 Runoff production, interception and attenuation*

Surface runoff is produced when rainfall is partitioned into plant uptake, soil infiltration or overland flow (Li et al., 2007), which can result in runoff generation by two mechanisms (Figure 2.1):

i. When rainfall intensity exceeds the soil infiltration rate (Horton, 1933) and results in *infiltration excess* overland flow (also known as Hortonian overland flow); or
ii. Where soils become saturated and can provide no further storage, which results in *saturation excess* overland flow (Dunne and Black, 1970).

Interception and attenuation of runoff are defining factors of an NFM measure as disconnection and storage of overland flow are part of the NFM definition (SEPA, 2016a). Attenuation of overland flow can be achieved through water storage or by a reduction in velocity by frictional resistance exerted by vegetation, otherwise known as hydraulic roughness. Riparian buffer strips are advocated for their ability to provide hydraulic roughness and slow runoff to trap sediments, allowing infiltration and filtration nutrients or pollutants (Borin et al., 2010). In-channel riparian vegetation has been shown to create hydraulic roughness which slows conveyance and velocity of streamflow (Darby, 1999; Environment Agency, 2014b; Tabacchi et al., 2000). But riparian buffer strips extend beyond the channel onto the landscape with varying widths and understanding how these spatial areas intercept runoff and function hydrologically is pertinent to addressing research gaps.

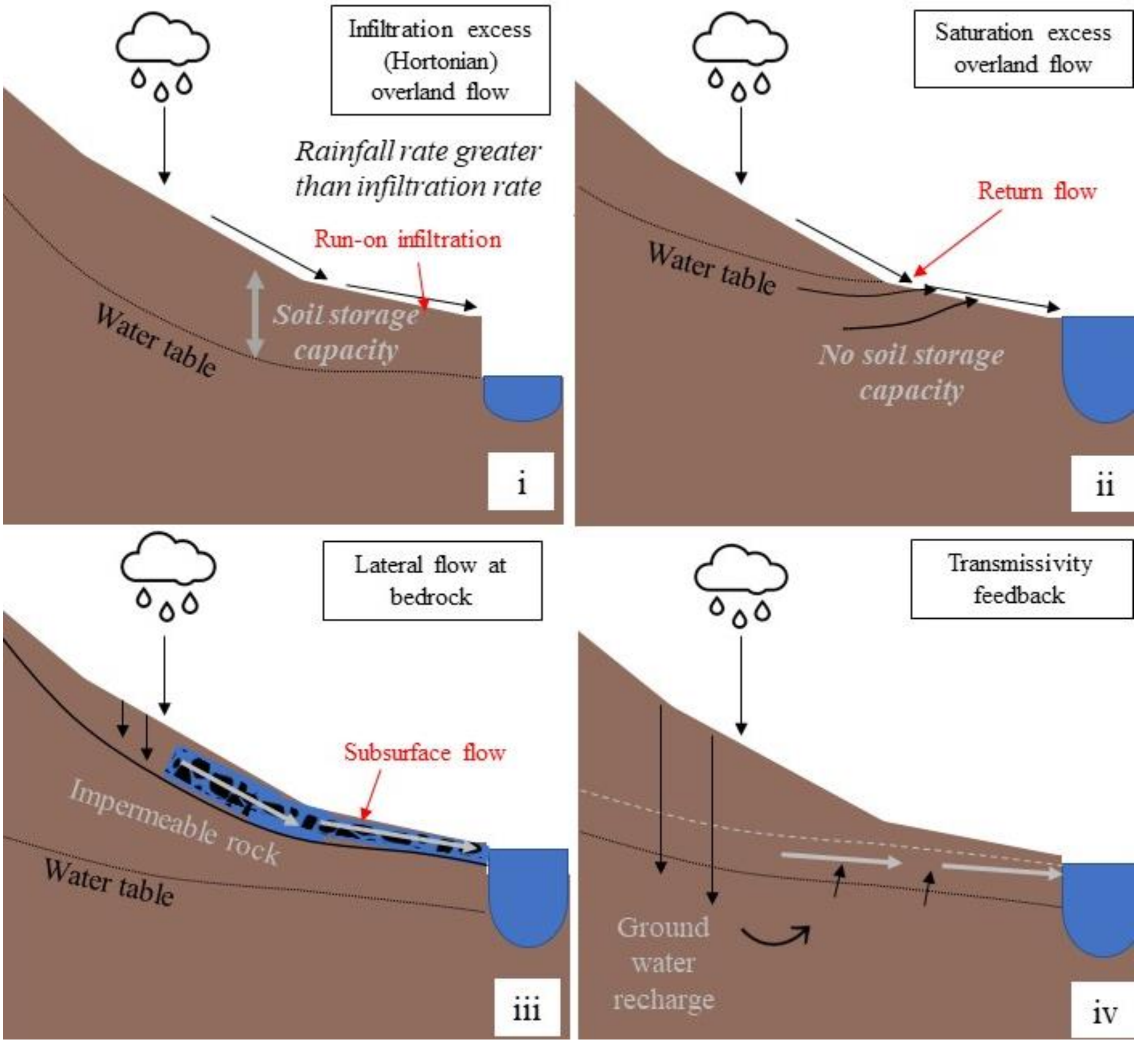



Figure 2.1 Illustration of infiltration excess (Hortonian) overland flow (i) and saturation excess overland flow (ii) processes. Hillslope subsurface processes of lateral flow at bedrock (iii) and transmissivity feedback (iv) demonstrate mechanisms of subsurface runoff contributions to the channel (Images provided by The Noun Project Inc). Adapted from Rinderer and Seibert (2012) and Ross *et al.* (2017).

The presence of buffer vegetation will increase hydraulic roughness (Environment Agency, 2017a), which, in turn, attenuates overland flow to enable infiltration to occur (Dillaha et al., 1989). Underlying soils serve a hydrological function in partitioning rainfall into infiltration and runoff and those underlying riparian zones will be an important hydrological control (Li et al., 2007). Studies by Bharati et al. (2002) and Stutter and Richards (2012) examined riparian soils and indicated greater infiltration capacities compared to adjacent managed land. However, de Sosa et al. (2018a) contested this and found riparian soils to be of similar condition as those in the adjacent land. Wagena and Easton (2018) propose riparian buffer strips can become overwhelmed by increased precipitation intensities (and therefore runoff volumes), especially as climate change intensifies storm events. Understanding the role of event conditions and effectiveness of buffer strip runoff attenuation is therefore an important research area but requires the inclusion of the complex interactions between other runoff affecting elements (e.g. land use and hillslope hydrology).

Precipitation is a driving factor in runoff generation and connectivity between hillslopes and riparian zones. This study aims to understand the rainfall event and land management conditions in which runoff enters the buffer strip on a hillslope.

### *2.2.2 Hillslope hydrology*

Hillslope hydrological processes can have an influence on overland flow generation and the subsurface storage capacity of riparian zones. Hillslope hydrology is a complex research area not focused on in this research but is summarised here due to the importance of having a background understanding of the influence on overland flow in riparian zones.

Subsurface hydrological processes on a hillslope are affected by slope gradient, geology, soil properties and hydraulic properties which vary spatially and temporally (Angermann et al., 2017). As identified by Van Tol et al. (2011), key subsurface flow paths on a hillslope include: macropore flow, lateral flow, return flow and flow at the interface of soil with the bedrock (Figure 2.1). Land use change may alter these fast near surface flows, which can also be intercepted by field drains. O'Connell et al. (2007) for example, stresses the influence of arable land use on soil structure, which causes compaction and can lead to an alteration of subsurface throughflow in upper soil layers. Surface and subsurface soil compaction can result in increased overland flow as well as create fast near surface flows (Brus and van den Akker, 2018). These fast near surface flows are a consequence of subsoil compaction creating preferential flow paths at the pan layer (Etana et al., 2013). The location of field drains may intercept these subsurface flow paths. However, the impact of field drains on flood risk are inconclusive (Blanc et al., 2012)and thereby may negate or exacerbate subsurface runoff. A study by Ocampo et al. (2006) discovered hydrological connectivity between the hillslope and riparian zone was transitory and dictated by a perched water table which would occur at a seasonal timescale. Compared to the highly responsive riparian zone, the hillslope can have a delayed formation of a saturated zone in response to rainfall, which must exceed a threshold before subsurface hydrological connectivity initiates (Ocampo et al., 2006). Weiler and McDonnell (2004) summarise four key established concepts of hillslope hydrology:

- *Lateral flow at bedrock* occurs where soils are thin, slopes are steep, and bedrock is impermeable (or has low permeability). Infiltrating water is perched above the impermeable bedrock layer creating a subsurface preferential flow path where lateral flows rapidly occur at the bedrock and saturated soil interface, contributing to runoff to the river channel (i.e. image iii in Figure 2.1).
- *Transmissivity feedback* is when groundwater is quickly recharged due to rapid infiltration and raises the water table into a highly permeable soil zone which initiates fast lateral flows downslope to the river channel (i.e. image iv in Figure 2.1).
- *Translatory flow* due to pressure waves: when 'new rain' infiltrates it exerts more hydraulic pressure on the existing water in the soil column of the hillslope, displacing existing stored water which eventually becomes storm flow (Hewlett and Hibbert,

1967; Renée Brooks et al., 2010). The ‘old’ water contributes to storm flow rather than the ‘new’ water.

- *Interflow*: the rapid movement of lateral subsurface flows through the upper litter layer of the soil column.

Early literature underpins that the lower 25% of slopes have higher soil moisture (Helvey and Hewlett, 1962) and at the toe-slope (the base of the slope) overland flow can be a result of return flow (See illustration (i) in Figure 2.1 and Figure 2.2) where subsurface water is forced to re-emerge, or where surface soil layers are saturated (Chorley, 1978; Kirkby and Chorley, 1967) (Figure 2.1). More recently however, the complexities of hillslope hydrology have been highlighted. For example:

- Freer et al. (2002) identified bedrock (rather than surface topography) controls the lateral movement of water downslope;
- Vidon and Hill (2004) conversely recognised the substantial influence of topography on subsurface flows in riparian zones (e.g. >5% slope demonstrated subsurface flow in the direction of the steepest slope gradient);
- Tromp-van Meerland and McDonnell (2006) highlighted that precipitation thresholds determine the initiation of hillslope lateral flows;
- McDonnell (2003) indicated hillslope runoff contributions are propagated from rising water tables in riparian zones (which could be affected by toe-slope lateral flow or perched water table, transmissivity or a ‘saturated wedge’);
- McGlynn and McDonnell (2003) found riparian water to be discharged at a similar rate to hillslope runoff when the riparian storage volume is exceeded by the inputs from the hillslope, although some hillslope runoff has been observed to bypass the riparian zone due to preferential flow paths; and
- Jensco and McGlynn (2011) highlight the importance of understanding hydrological connectivity between the hillslope-riparian-stream continuum to identify problematic runoff generation source areas.

Toe-slope areas are often where riparian buffer strips are situated, and soils here are inherently wetter with less storage capacity. Less soil storage capacity at the toe-slope can be influenced by additional water influxes from variable source areas (Dunne and Black, 1970) of translatory flow, interflow, lateral flow or transmissivity feedback (Figure 2.1), which are likely to exacerbate overland flow generation either within the riparian zone or at the interface between field and buffer.

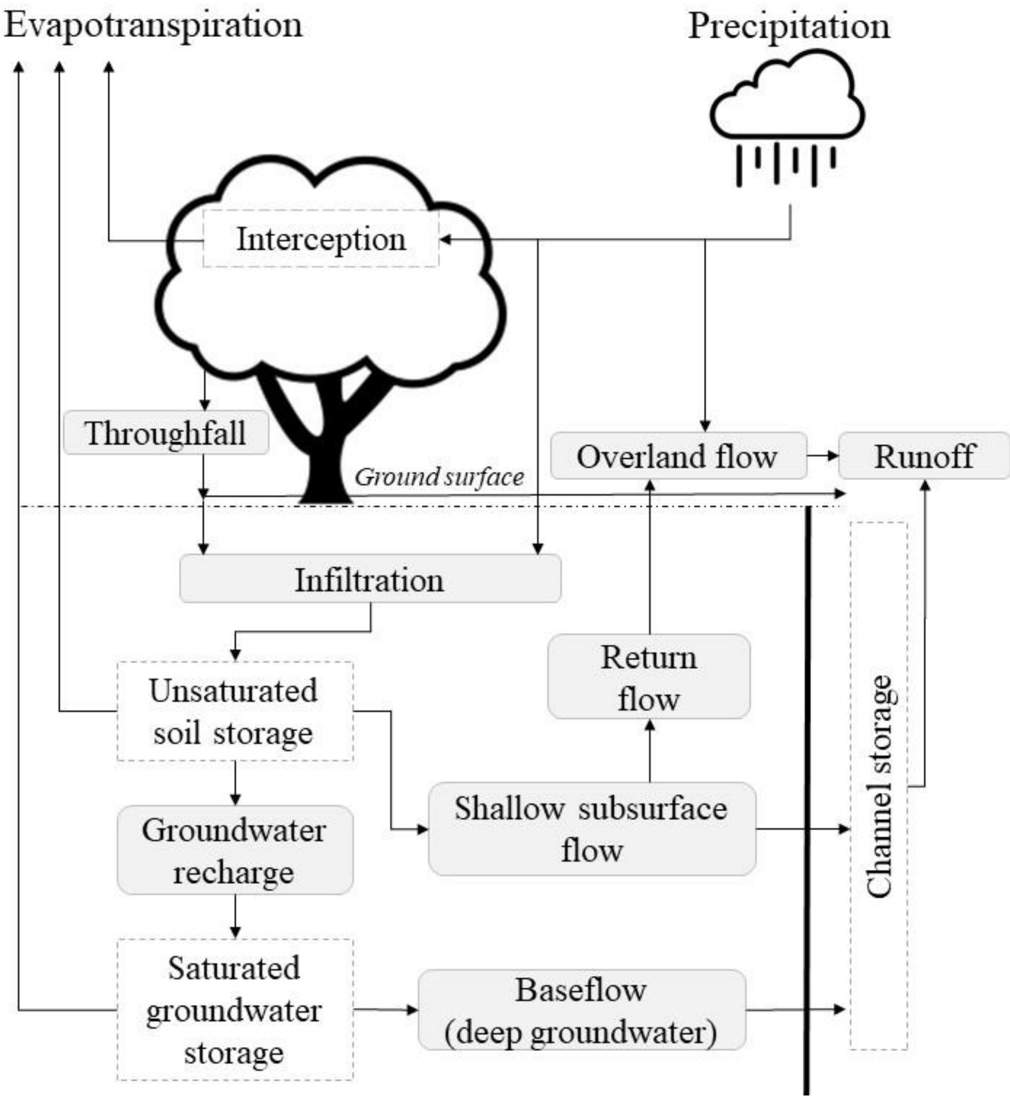



Figure 2.2 Hydrological cycle demonstrating the flow pathways (grey boxes) and storage locations (white boxes) and how they are connected to producing overland flow/runoff.

### *2.2.3 Overland flow paths and microtopography*

According to the EA (Environment Agency, 2017a), field studies ascertaining the ability of riparian buffer strips to attenuate overland flow are limited. Overland flow is often assumed to occur as sheet flow (where runoff is spread as a thin layer moving downslope) and to enter riparian buffer strips perpendicularly (Emmett, 1978). However, it can also occur as a concentrated flow (also referred to as converging flow) where: a slope decreases (e.g. at the toe-slope of a hill); topography converges; or where soil is shallow on a slope and becomes saturated (Hallema et al., 2016; Steenhuis et al., 2005). Dillaha et al. (1989) demonstrated concentrated field runoff flowed through partial areas of buffer strips. Several studies identify microtopography to generate concentrated flows both in adjacent fields and inside riparian buffer strips, significantly affecting runoff attenuation capabilities (Dabney et al., 2006; Dąbrowska et al., 2018; Dillaha et al., 1989; Helmers and Eisenhauer, 2006; Hénault-Ethier et al., 2017; Lee et al., 2003; Stehle et al., 2016). For example, Lowrance et al. (1997) observed both furrows (created by field machinery) and sediment build up at the interface between the field and buffer strip resulted in overland flow bypassing a grassed riparian buffer strip. Consequently, runoff entered the buffer strip only when overland flow became concentrated. The build-up of sediment berms at the field-buffer interface was demonstrated by Pankau et al. (2012) to be positively correlated to concentrated flow path size (cross-sectional area) and be prevalent in agricultural watersheds.

In-field concentrated flows could result in riparian buffer zones not receiving any overland flow. When concentrated flows are received, Dosskey et al. (2002) observed higher depths and velocities. Shallow slow-moving water (e.g. sheet flow) inside a buffer strip is required for attenuation, infiltration and sediment deposition (Dosskey et al., 2002). Concentrated flows inside buffer strips may result in buffers being rendered ineffective for sediment retention, water quality improvements or NFM (Dosskey et al., 2002). Nevertheless, Lowrance et al. (1997) and Dosskey et al. (2010) conclude buffer strips with grass vegetation to be most effective at dispersing concentrated flows into sheet flow, which enhances sediment trapping and provides greater attenuation to enhance infiltration. Grassed buffer strips would therefore be best targeted to areas where concentrated flows occur. However, these concentrated flow pathways will vary. For example, rotational arable land management will produce different microtopography following planting or harvest cycles. Irrespective of in-field microtopography, sediment berms at the field-buffer interface will remain relatively constant unless removed by active management of riparian buffer strips.

**Field studies monitoring overland flow**

Methods adopted in studies to capture overland flow generally involve collection bottles or tanks. A study by Stehle et al. (2016) for example, assessed pesticide transport in surface runoff through riparian buffer strips using buried sample bottles; and also identified the issue of concentrated flow paths generated from erosion rills. These concentrated flow paths in the erosion rills resulted in the buffer strip being ineffective at retaining pesticides (Stehle et al., 2016) and suggest the ability of the buffer strip to attenuate overland flow was compromised due to erosion rills. The use of buried collection bottles is not appropriate for this study as it is unable to quantify (over long term) event-based surface runoff entering a riparian buffer strip.

The study by Hénault-Ethier et al. (2017) collected surface water by utilising buckets buried into the soil perpendicular to buffer strips and recording volumes manually over eight site visits in 2011. One of two experiment sites demonstrated a significant reduction in runoff volume (on average by 0.5 Litres) by comparing collected surface water at the edge of the field to that situated close to the river. The method adopted in this study for collection of surface runoff does not allow for event-based analysis of overland flow volumes. Nonetheless, this study also identified issues of concentrated flows and recognised that a fraction of the buffer strip area was being effective; thereby prompting the proposal of targeting larger buffer widths where concentrated flows occur.

A study in Pontbren in Wales (Wheater et al., 2008) examined the impact of land management (grazing, tree planting and no grazing) on hydrological response. Surface runoff was measured by installing a gutter to capture overland flow from a 2.5 m x 10 m plot, which flowed to a buried tipping bucket gauge. This method enabled event-based monitoring of surface runoff at 10-minute intervals and is relevant to this study as a basis for the design of a field experiment to capture runoff at the edge of the buffer strip. A key finding from this study was that tree planting and exclusion of sheep grazing resulted in soil infiltration rates being 67 times greater (Marshall et al., 2014).

### *2.2.4 Multiple benefits of riparian buffer strips*

There is a significant evidence base that riparian buffer strips fulfil the multiple benefit functions of an NFM measure. Hydrological benefits include greater infiltration, hydraulic roughness and interception of overland flow, which have been outlined in Sections 2.2.1, 2.2.2, and 2.2.3. Riparian buffer strips fulfil other multiple benefits which include: bank stabilisation and reduced erosion (Hubble et al., 2010; Pollen-Bankhead and Simon, 2010); filtration of nutrients in diffuse pollution (Collins et al., 2009; Krovang et al., 2012; Ranalli and Macalady, 2010; Syversen, 2005; Wenger, 1999), reduced heavy metals and contaminants (pesticides/herbicides) (Pavlović et al., 2016; Schulz et al., 1998), provision of habitat and species diversity (Naiman et al., 2013; Stockan et al., 2012), hydraulic roughness (Croke et al., 2017; Darby, 1999), and reduced sedimentation (Deasy et al., 2011, 2009; Muscutt et al., 1993; Silgram et al., 2010).

According to Stutter et al. (2012), riparian buffer strips and the multiple functions they carry out are widely researched, but restricted to mostly single riparian functions and flood risk studies are scarce (Environment Agency, 2017a). There is a need for science to address the interdisciplinary research gap in riparian buffer strip research by incorporating flood risk (Stutter et al., 2012). This study aims to consider both runoff attenuation for flood mitigation and a selected multiple benefit of riparian buffer strips.

### *2.2.5 Optimal riparian buffer strip width*

An abundance of research exists which assess the most effective width of riparian buffer strip for the purpose of disciplines other than flood risk. Buffer width suggestions from earlier literature are provided by Wenger (1999) who summarises existing research at that time. Wenger (1999) outlines optimal buffer widths suggested from studies on sediment trapping (4.6-30 m), phosphorus retention (8-28 m), total nitrogen filtration (4.6-9.1 m), wildlife and habitat (15-100 m). The suggested effective buffer widths vary greatly depending on the purpose of buffer or perspective of the research. Reflecting Wenger's (1999) literature summaries, a more recent analysis of buffer width literature by Collins et al. (2009) recognises that all studies on buffer width are relevant to the local circumstances and buffer width cannot be implemented as a one-size-fits-all. Collins et al. (2009) provides a comprehensive overview of buffer width literature indicating each study's recommended width (which varied from 0.7-91 m) in relation to slope (from <2% to 20%) and the percentage of efficiency at reducing phosphorus, sediment, nitrogen, pesticides and faecal indicator organisms. The authors concluded optimal buffer width is site specific and should be implemented using a targeted approach.

A study by Phogat et al. (2019) assessed buffers of 20-60 m but critically indicated the necessity of considering adjacent crop types and runoff preferential flow paths before settling on a specific width. It is made clear from Wenger (1999) that effective buffer widths depend on a multitude of factors: soils, slope, land use, vegetation, rainfall and contributing area. Yet, Collins et al. (2009) insightfully recognises the need to be realistic and accept localised constraints rather than implementing an optimal buffer width for maximum reduction in sediments and nutrients. Literature has supported the implementation of targeted buffer width (suited to localised conditions and concentrated flow paths) rather than an arbitrary uniform buffer width (Collins et al., 2009; Dillaha et al., 1989; Phogat et al., 2019; Tabacchi et al., 2000; Wenger, 1999). Yet, riparian buffer strips continue to be implemented uniformly, which is likely due to the lack of an efficient tool to rapidly estimate optimal widths (tailored to site-specific conditions). If riparian buffer strips were to become a readily utilised NFM measure, early consideration of variable targeted buffer widths could enhance their effectiveness.

### *2.2.6 Catchment distribution*

Studies tend to focus on *upland* or *floodplain* riparian buffer strips rather than catchment-wide riparian buffer strips (in any discipline). There seems to be an assumption that management of fluvial flood hazard can be achieved in the floodplain, implying riparian buffer strips in uplands are less effective. For example, Wenger (1999) and Croke, Thompson and Fryirs (2017) propose out-of-bank flows are attenuated more effectively when riparian buffer strips extend the floodplain considerably. In contrast, Parkyn (2004) emphasises the role of riparian buffer strips on floodplain is the slow out-of-bank flows and highlights the hydrological connectivity between the landscape and smaller streams in headwaters. Thus, greater opportunity to intercept hydrological pathways and slow runoff velocities in headwaters for which riparian buffer strips could be beneficial. Syverson (2005) for example, indicated the importance of retention time by slowing the velocity of surface runoff in riparian buffer strips to maximise the interaction period between vegetation and soil for nutrient removal. The concept emphasises the potential for riparian buffer strips to attenuate runoff from a flood risk perspective. This study aims to understand the ability of a case study riparian buffer strip to receive and attenuate runoff in an upland stream, as well as identify opportunities to maximise their NFM functionality.

### *2.2.7 Temporal effectiveness*

Riparian buffer strips require time for vegetation to become established, which will vary depending on vegetation type (e.g. shrubs and trees will take longer to establish than grass species). Buffer strip effectiveness is therefore not instant and requires lead-in time for vegetation establishment and subsequent benefits. For perennial or deciduous vegetation, autumn and winter periods will inhibit a riparian buffer strip's effectiveness as an NFM measure. Wenger (1999) indicates seasonal loss of foliage and die-back in riparian buffer strips can influence interception of rainfall, evapotranspiration and hydraulic roughness.

The effectiveness of riparian buffer strips as an NFM measure could either improve or deteriorate with time as climate change impacts the hydrological cycle. Wagena and Easton (2018) for example, hypothesise more intense rainfall events could overwhelm riparian buffer strips. Yet, the authors also propose higher temperatures and longer growing seasons could more rapidly establish riparian buffer vegetation and extend the growing season. The longevity of riparian buffer strips being an effective NFM measure is uncertain over longer time periods when climate change may have an impact.

## 2.3 Agricultural land management and runoff generation on hillslopes

Agricultural land management changes are diverse and complex and occur at a range of spatial and temporal scales. Intensification of agriculture following World War II was encouraged to meet food demands and resulted in the removal of hedgerows, extensive land drainage, larger field sizes and the increasing use of heavy mechanised vehicles (Nicholson et al., 2012; O'Connell et al., 2007). According to the UK Department for the Environment, Fisheries and Rural Affairs (Defra) (O'Connell et al., 2004), soil capacity has reduced due to soil degradation from increased stocking densities, autumn-sown cereals, increased maize crops and use of fine seedbeds. Several studies (Hess et al., 2010; McIntyre and Marshall, 2010; O'Connell et al., 2004; Parrott et al., 2009) have indicated agricultural land management affects flood risk and increases surface runoff at farm scale. Evidence of impacts at catchment scale are lacking (Dadson et al., 2017). Agricultural intensification has led to the creation of plough lines, tramlines and tyre tracks, as well as increased soil compaction, all of which enhance surface runoff and alter flow pathways (Deasy et al., 2014; Silgram et al., 2010) and can contribute to downstream flooding (O'Connell et al., 2007; Wheater and Evans, 2009; Wilkinson et al., 2014). However, Deasy et al. (2014) recognised those land management practices that exacerbate flooding can be targeted and adapted to mitigate the generation of surface runoff, which may involve the use of additional measures where conditions are appropriate (i.e. ponds and wetlands) (Duffy et al., 2016). Agricultural land management has been identified as an integral element of FRM (Environment Agency, 2017a).

Overland flow naturally takes the path of least resistance when flowing downslope and is known to be influenced by gradient of land, slope length, vegetation and microtopography (Liu and Singh, 2004). Intensive agricultural land management can increase runoff at local and farm scale (O'Connell et al., 2007) and management practices can result in microtopographies that concentrate overland flows into rills (Baiamonte and Singh, 2015). The two-fold influence of intensive land management practices and hillslope hydrology on runoff generation is a concern and measures to mitigate the impact on flood risk are essential.

### *2.3.1 Cultivation practices and bare soils*

Soils serve a vital hydrological function in partitioning rainfall into infiltration and runoff (Li et al., 2007). Soil moisture and infiltration are intrinsically linked whereby higher soil moisture reduces the volume of water able to infiltrate (Gray and Norum, 1967). Key soil properties however, control how water is transported through the soil (Figure 2.3) for example: structure; pore volume and distribution; bulk density; saturated/unsaturated hydraulic conductivity; infiltration capacity; and field capacity (Bormann and Klaassen, 2008). These same properties are impacted by agricultural land use, for example: intensive agriculture can increase bulk density and reduce hydraulic conductivity due to compaction from mechanised vehicles, impacting the conductivity and storage of soil water (Bormann and Klaassen, 2008). Soil degradation occurs as a result of cultivation practices, which increases soils vulnerability to compaction (O'Connell et al., 2004). This repetitiveness of cultivation can also create a compacted 'pan' layer, which is less permeable, and is especially prevalent in areas where machinery tracks have repeatedly compacted the soil (O'Connell et al., 2004).

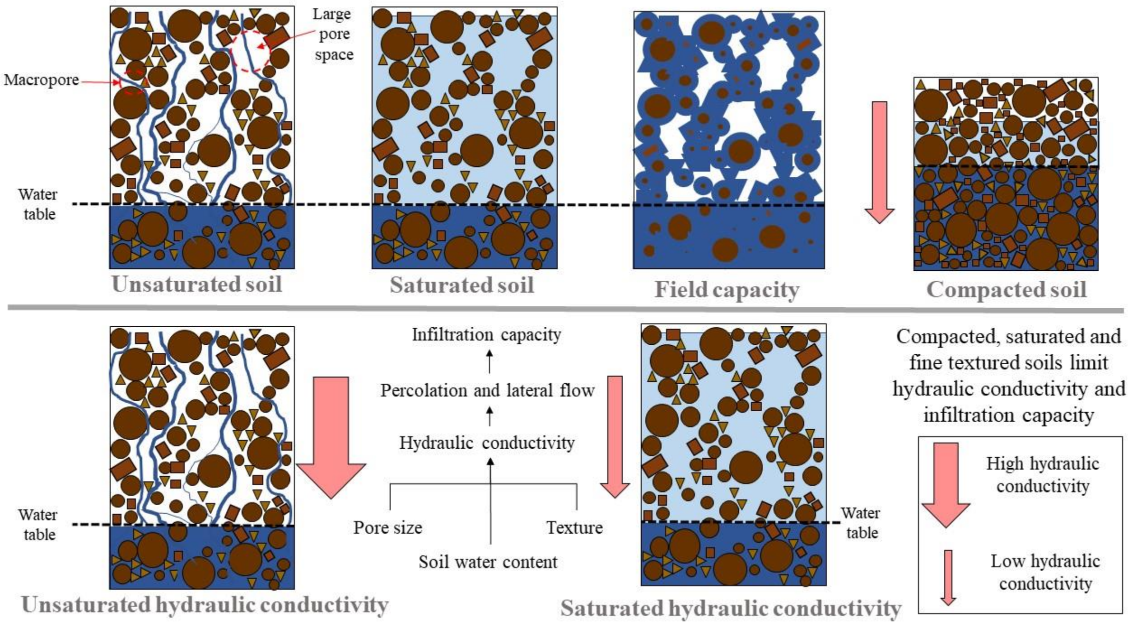



Figure 2.3 Downward water transport through unsaturated, saturated and compacted soil. Arrow size represents degree of hydraulic conductivity: large arrow is high conductivity and small arrow is low hydraulic conductivity. Adapted from FLOODsite (2008), Leibowitz *et al.* (2018); and Rinderer and Seibert (2012).

A study by Withers et al. (2007) identified a trend of a 5-fold increase in runoff volumes when crops were sown, and subsequently cultivated, later than usual. The study made a clear conclusion that surface sealing of soils, late sowing of crops and inappropriate cultivation timing (when soils were wetter) increased compaction and subsequent runoff volumes (Withers et al., 2007). Bare soil increases runoff and erosion of soil and row crops also exacerbate this, especially if planted running up and down a hillslope (O'Connell et al., 2004). Although, these impacts are evident only at local scales (O'Connell et al., 2007) and their influence at catchment scale is not apparent (Environment Agency, 2017a).

With respect to arable land management, Chamen et al. (2003) outline ways in which management practices can influence soil compaction and in turn, impact runoff generation, for example:

- Pressure on soil from the weight agricultural machinery and the number of passes across the land can cause soil compaction. Soil structure becomes affected as pore sizes are reduced, limiting infiltration capacity and hydraulic conductivity. In turn, runoff is generated more rapidly during rainfall events.
- Cultivation practices depend on the crop type, which dictates the timing and depth of cultivation. Ploughing or harvesting in wet conditions, especially in the late autumn or early spring, exacerbates soil compaction and runoff generation. Root crops (e.g. beets or turnip) require deeper ploughing and heavier machinery, likewise increasing soil compaction.

Soils and hydrology are also affected by other interacting conditions including season, weather conditions, topography, groundwater, soil and geology. The complex interactions between these conditions and arable land management can combine to create circumstances where runoff generation is exacerbated (Environment Agency, 2017a). For example, a late autumn harvest on brown forest soil with gleying on sloping land during wet conditions would result in greater soil compaction and increased runoff.

Runoff generation from land management can be mitigated by using measures which aim to improve soil structure and minimise compaction, which in turn, improves infiltration and soil water capacity. Types of measures to mitigate the impact of land management on runoff generation include:

- Minimum tillage (also known as *conservation tillage*): minimises deep ploughing activity to safeguard soil structure and in turn, improve infiltration and provide hydraulic roughness (from longer crop/stubble coverage) (Quinton and Catt, 2004; Stevens et al., 2009). Nevertheless, there is limited evidence of the effectiveness of minimum tillage (Deasy et al., 2009; Stevens et al., 2009) and cover crops (O'Connell et al., 2004).
- Cover crops: crops grown in between standard crop production periods to protect soil from erosion and improve soil structure (Blanco-Canqui et al., 2015)
- Contour ploughing: fields are prepared and sown with crops where machinery and plough lines follow the contour of the land rather than up and down slope. This mitigates the creation of downslope direction overland flow paths (Lane et al., 2007; O'Connell et al., 2004; Quinton and Catt, 2004).

- Subsoiling: breaking up of deeper soil that has become compacted to increase infiltration and improve soil structure.

### *2.3.2 Influence of microtopography created by farm traffic*

There are numerous studies (Boardman et al., 2003; Chamen et al., 2003; Dadson et al., 2017; Environment Agency, 2017a; Li et al., 2007; O'Connell et al., 2007, 2004; Schwab et al., 1993; Silgram et al., 2010; Withers et al., 2006) which have determined farm traffic tramlines or wheelings to increase surface runoff. Tramlines function as markers for fertilisation spraying but the weight of repeated farm traffic compacts the soil, which can result in high velocity flow paths and the formation of rills (Deasy et al., 2009; Withers et al., 2006). The inherent compaction of tramlines on surface and subsurface soil layers leads to rapid surface and near surface runoff. Field drains may intercept these subsurface flow paths however, their impact on increasing flood risk is hitherto inconclusive and depend on localised soil conditions (Blanc et al., 2012). Quinn et al. (2008) proposed hump or channel cross drains as management measures, which cut across the tramlines and divert overland flow. However management measures are also proposed by O'Connell et al. (2004):

- Reduce pressure on the soil by decreasing tyre pressures and loads, as well as increasing tyre width.
- Ensure soil conditions are suitable for heavy machinery. Wetter soils will be more susceptible to compaction. If delaying the use of machinery (where possible) during unfavourable soil conditions, this should be considered.
- Use spiked tyres to create cracks in the soils to allow infiltration.
- On steep slopes, mole ploughing can be effective at diverting runoff away from tramlines.

## 2.4 Hydrological modelling and model selection

Estimating how rainfall falling on a catchment transfers and relates to river flows can be achieved by using rainfall-runoff modelling. Hydrological models enable extrapolation of limited hydrological measurements to larger spatial and temporal scales to predict possible scenarios for example, the influence of climate change or land use change (Beven, 2012). These crucial strategic tools aid decision making and are applicable to numerous disciplines (e.g. water resources, flood risk, planning and hydro-ecology). There are several types of hydrological model and each have their applications, assumptions, computational effort, complexity, advantages and disadvantages. Beven (2012) outlines two main types of hydrological model:

- *Lumped models*: in general, considers a catchment as one 'blackbox' unit, which utilises averaged values for the whole catchment and is not concerned about spatial heterogeneities in the catchment. This type of model is not applicable to this study as spatial distribution of riparian buffer strips is being considered.

- *Distributed models*: predict flow processes across a range of spatial scales within a catchment. Catchments are delineated into a large number of smaller portions, either as a grid or hydrological response units (HRUs), where parameter values are estimated for each delineated portion and localised averaged values are predicted. Beven (2012) intimates distributed models are essentially a collection of smaller lumped models which are spatially distributed. The distributed model is most appropriate for this study as it is able to account for the spatial distribution of riparian buffer strips and estimate the spatial variability of their impact on flows.

Hydrological models can be deterministic: where one value is predicted as an output for a variable; or stochastic: where a range of multiple values are predicted to establish the uncertainty in value outputs (Shaw et al., 2011). All models are uncertain and being explicit in their capabilities is crucial to incorporate into decision making and practical applications. Uncertainty in hydrological models (especially distributed models) is a huge concern in terms of their ability to be transparent about parameter uncertainty (Wilkinson, 2009). The issue of uncertainty is addressed in Chapter 4 and Chapter 7 in relation to the specific model utilised for this study.

Two freely available, widely used, distributed models were considered for use in this study: TOPography based hydrological MODEL (TOPMODEL) (Beven and Kirkby, 1979) and Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998). TOPMODEL is a physically based distributed model able to simulate hydrological processes (e.g. overland flow, infiltration, evapotranspiration, and subsurface flows) in a watershed (Beven, 2012, 1997) at 1-24 hourly time steps. The principle approach of TOPMODEL is the creation of HRUs based on landscape topography and soil characteristics by grouping similar landscape pockets with similar hydrological properties and assuming the hydrological response of similar HRUs are equal to minimise computational resource (Metcalfe et al., 2018). Assumptions of TOPMODEL are:

- The water table is almost parallel to the surface and consequently, the hydraulic gradient is equivalent to the surface slope (Beven, 2012). This restricts the ability to apply the model in areas with very deep soils or where topography is overly flat or steep (Shaw et al., 2011).
- The assumption of the water table being in a constant steady-state of recharge over the full HRU (hillslope), which can be unrealistic in larger HRUs where heterogeneity is more likely (Metcalfe et al., 2015).
- Transmissivity can essentially be explained by a function of the localised storage deficit in the saturated zone (Beven, 2012).

However, the assumption of the continual connectivity of the water table across all upslope HRUs (Beven, 2012) is addressed in a new adaptation called Dynamic TOPMODEL (Beven and Freer, 2001a). This assumption was replaced using localised kinematic wave estimations (Metcalfe et al., 2015).

SWAT is equally a popular hydrological model used on an international scale. Semi-distributed and physically based, SWAT is mostly intended for evaluating agricultural land management impacts on runoff, sediment, and diffuse nutrient transport (Arnold et al., 2012b). SWAT can be applied at sub-daily (1-23 hours), daily, monthly and annual time steps. SWAT utilises the HRU approach to represent smaller areas of each sub-basin with homogenous soil type, land use and slope (Arnold et al., 2012b). Key assumptions of SWAT are:

- There is no connectivity between HRUs in the same sub-basin (Arnold et al., 2012a) therefore no runoff from one HRU can enter another without engaging the intricate resource intensive hillslope discretisation method to route overland flow (Arnold et al., 2010).
- The whole HRU responds in the same way despite spatial scale (Arnold et al., 2012a)
- Runoff is predicted to occur beyond a condition of baseflow and losses to the deep aquifer are enabled, which have no impact on channel flows (Beven, 2012)

Contrasting both models to select which was best to use in this thesis, both TOPMODEL and SWAT are semi-distributed, freely available, widely used, can produce GIS outputs, and are able to produce hourly resolution outputs, which are required for this research.

Despite their similarities, SWAT was selected over TOPMODEL for several reasons. The first being the user-friendly resources in the form of an ArcGIS interface, multiple google user group forums offering valuable support, extensive documentation and an existing database of generic land use and soil parameters. Secondly, riparian buffer strips are an agricultural land management measure and SWAT is specifically aimed at assessing agricultural processes and their impact on runoff and diffuse pollution (Beven, 2012). Lastly, this research was delivered in conjunction with The James Hutton Institute (JHI) and the ability to utilise the model from this study in further research at JHI to assess sediment and nutrient loads, as well as diffuse pollution, offered longer term purpose and relevance.

### *2.4.1 Modelling catchment-wide riparian buffer strips and their impact on flooding*

A recent synthesis of riparian research in the UK highlighted the lack of model based studies assessing flood risk and riparian buffer strips, but indicated this study (identified by a conference paper (McLean et al., 2013) indicating future modelling work) as being the only one in the UK (De Sosa et al., 2018b). In terms of the influence that riparian buffers have on hydrological processes at catchment scale, research is limited especially when directly focusing on flood risk. Although, SWAT studies assessing riparian buffer strips do so in terms of their impact on diffuse pollution, nutrient loads and sediment loads, echoing that of empirical studies of riparian buffer strips.

Nevertheless, there are a few research papers which assess methods relevant for modelling riparian buffer strips in SWAT that apply to surface runoff. Arnold *et al.* (2010) for example compares the three methods which can be adopted in SWAT for assessing the catchment scale impact of riparian buffer strips are: hillslope discretisation, sub-watershed discretisation and grid-cell discretisation (defined and illustrated in Figure 2.4). The comparison by Arnold *et al.* (2010) highlighted the following:

- Grid cell discretisation was excessively computationally intensive and required increased resolution of data inputs;
- Hillslope discretisation allowed riparian zones to be accounted for in distinct areas within their topographical position in the catchment;
- Sub-watershed discretisation did not reflect the 'cascade of flow' on hillslopes but at catchment scale, calibration demonstrated flows were similar for all three methods; and
- Validation implied hillslope discretisation was spatially detailed, but the sub-watershed discretisation method achieved an equivalent accuracy of flow predictions

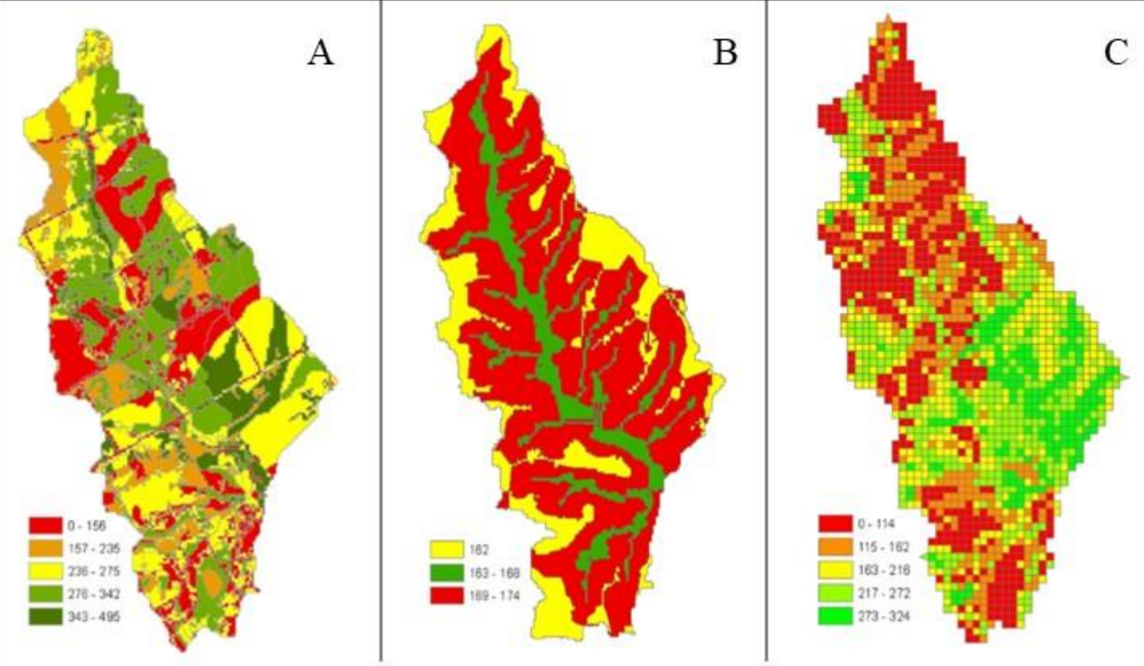
Although in relation to water quality, Sahu and Gu (2009) utilised the hillslope discretisation method to account for runoff passing through a riparian buffer strip from the crop of an adjacent HRU but the method was unable to account for concentrated overland flow.

This thesis aims to understand the impact of riparian buffer strips implemented across the whole catchment on peak flows at catchment scale by utilising SWAT. Selection of the appropriate SWAT method to adopt was a balance of input data resolution, quality of outputs compared to time resource required, and the purpose of the modelling. Sub-watershed discretisation was utilised for the following reasons:

- Arnold *et al.* (2010) highlighted SWAT outputs using this method were similar at catchment scale to grid cell and hillslope discretisation. Sub-watershed discretisation is less time intensive and achieves a similar quality of output to the other methods.
- Hillslope discretisation is useful for representation of hillslope scale processes. This study examines hillslope scale using a field study and aims to use SWAT to assess larger spatial scale impacts of riparian buffer strips on peak flows. Therefore, sub-watershed discretisation is most appropriate.
- Arnold et al. (2012a) explains sub-watershed discretisation maintains realistic natural flow paths and boundaries.
- Grid cell discretisation requires higher resolution data inputs and greater computational effort, which also requires added time resource.

The SWAT Riparian Ecosystem Management Model (SWAT-REMM) is not freely available and a developing add-on to SWAT that assesses riparian buffer strip impact on diffuse pollution (Ryu et al., 2011b, 2011a; Zhang et al., 2017). This could be a promising addition to SWAT for evolving studies into the impact of riparian buffer strips on surface runoff once fully functional and freely available.

| **Sub-watershed discretisation definition** | **Hillslope discretisation definition** | **Grid cell discretisation** |
|---|---|---|
| • Delineates catchment into sub-basins and subsequent HRUs which consist of homogenous soil and land use combinations.<br>• HRU hydrological loads are summed and in turn, sub-basin loads are summed.<br>• Net loads for each sub-basin are routed to the stream network.<br>• Method preserves realistic natural flow paths, hydrographical boundaries and channels. | • Delineates catchment sub-basins to have one land use and one soil per sub-basin<br>• Routes overland flow from one sub-basin into the land area of another adjacent sub-basin, rather than routing directly to the channel.<br>• Incorporates more detail to allow hillslope processes to be modelled. | • Delineates catchment into (much smaller) sub-basins and subsequent grid cell.<br>• Grid cells area of homogenous soil, land use and slope.<br>• Runoff is routed from one grid cell to another and summed for the sub-basin<br>• Captures high resolution of spatial heterogeneity with greater computational requirements |




**Average annual surface runoff (mm) for each discretisation method**

Figure 2.4 Adapted from Arnold et al. (2010) showing the difference in average annual surface runoff (mm) for the sub-watershed discretisation (A), hillslope discretisation (B), and grid cell discretisation (C) methodologies in SWAT.

### *2.4.2 SWAT at field scale and catchment scale*

At catchment scale, a hydrological model can generate satisfactory stream flows at the catchment outlet yet be unrealistically representative at smaller spatial scales within the same model (Rajib et al., 2018); known as equifinality (Beven, 2012; Beven and Freer, 2001b). Spatial and temporal scales of a hydrological model should therefore correspond to the purpose of the model as this will impact model accuracy (Baffaut et al., 2015). This study for example, aims to assess *catchment* scale impact of riparian buffer strips implemented across the whole catchment therefore, calibration and output analysis should occur at catchment scale. Perception of spatial scale is subjective as 'field' scale SWAT studies have been conducted for catchments of varying sizes for example: 375.3 $km^2$ (Merriman et al., 2019), 50 $km^2$ (Merriman et al., 2018), 38 $km^2$ (Briak et al., 2019), and 6.23 $km^2$ (Arabi et al., 2006). Nevertheless, Baffaut et al. (2015) defines the spatial scale of hydrological models and identifies relevant models that can be implemented at each spatial scale (Table 2.2). Baffaut et al. (2015) emphasises semi-distributed models like SWAT, which aim to represent spatial and temporal heterogeneity of landscapes, are more appropriate for catchment scale (i.e. watershed or river basin scale in Table 2.2). Expecting a catchment scale model to be representative of field or smaller scale is unrealistic and Baffaut et al. (2015) emphasises that additional models (i.e. those in Table 2.2) should be employed according to their suited spatial and temporal scale. SWAT is the most appropriate model for this study as it aims to understand catchment scale impacts of land management changes.

Table 2.2. Adapted from Baffaut et al. (2015) to define different spatial scales of hydrological models and identify relevant models to be applied at each spatial scale.

| ***Spatial scale*** | ***Size*** | ***Appropriate model*** |
|---|---|---|
| Point | <1 $m^2$ | HYDRUS and TOUGH2 |
| Plot or hillslope | 1 – 100 $m^2$ | *Plot:* EPIC, RZWQM, and Daisy<br>*Hillslope:* KINEROS and WEPP |
| Field or small catchment | 100 $m^2$ – 50 ha | APEX, WEPP, DRAINMOD, and MODFLOW/MT3DMS |
| Watershed | 50 ha – 50 $km^2$ | SWAT, WARMF, HSPF, MIKE-SHE |
| River Basin | >50 $km^2$ | |

## 2.5 Ecosystem services

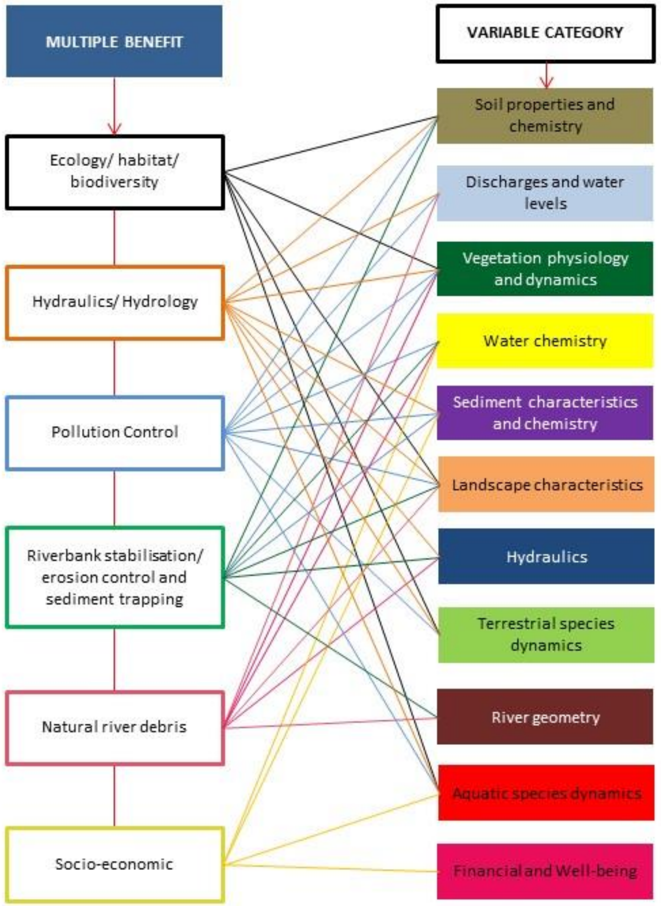
Ecosystem services are defined as the direct and indirect contributions of ecosystems to human well-being (TEEB, 2012). Ecosystems are dynamically complex interacting units at various scales in which living organisms interact with one another chemically, physically or biologically, and with abiotic factors; creating natural processes that enable intricate ecological balances within one system (POST, 2007; TEEB, 2012).

These ecosystems provide 'goods' and 'services' that humans benefit from (and depend on) (POST, 2007) and have been categorised by the MEA into: provisioning (e.g. drinking water), regulating (e.g. floods), cultural (e.g. recreation) and supporting services (e.g. nutrient cycling) (Millennium Ecosystem Assessment, 2005). Table 2.3 outlines the MEA classifications of ES with examples specific to river systems and land management. Other classifications exist for example, the UK National Ecosystem Assessment (UKNEA) uses: primary and intermediate services (e.g. soil formation and nutrient cycling), final services (e.g. food production) and goods/benefits (e.g. cereals or vegetables) (Morris and Camino, 2011, Mace et al., 2011, Haines-Young and Potschin, 2009, Fisher et al., 2009, Fisher and Turner, 2008). However, the MEA is more widely used in the international community and will be used for this study to enable wider application.

Table 2.3. Ecosystem service classification of the Millennium Ecosystem Assessment (2005) with supporting examples.

| ***Ecosystem Service Classification*** | ***Examples of river and land management ecosystem services*** |
|---|---|
| Provisioning | Habitat and biodiversity, clean air, drinking water, flood protection and irrigation |
| Regulating | Flood regulation, disease (and health) regulation, climate regulation, nutrient cycling, water quality (regulates pollution), erosion control & water cycle regulation |
| Supporting | Nutrient cycling, biogeochemical cycling, filtration of pollutants, sediment transport and deposition, energy and carbon transfer & soil formation |
| Cultural | Aesthetics, recreation (e.g. fishing and swimming), well-being |

Interactions and dependencies between the environment (biotic and abiotic), society and the economy are the essence of the ES concept and it has been advocated that the ES approach has potential to be effective in evaluating NFM multiple benefits (Frontier Economics Ltd et al., 2013; Iacob et al., 2012). The multiple benefits of NFM measures could be examined as multiple ES and examined utilising an ES approach, enabling a holistic appraisal of their multiple benefits (for example the framework in Figure 2.5 from McLean et al. 2013). There is a rapidly growing literature base on ES and how the ES approach can be applied to the appraisal multiple benefits of NFM (Brauman et al., 2007; Collentine and Futter, 2018; Dittrich et al., 2018; Iacob et al., 2012; Keesstra et al., 2018; Maitre et al., 2007; Nedkov and Burkhard, 2012; Posthumus et al., 2010). Although Dittrich et al. (2018) acknowledge the scarcity of studies which assess flood benefits in conjunction with other benefits and ES. The lack of a unified cohesive methodology for approaching the incorporation of ES into decision making is glaringly absent (Böck et al., 2018; Costanza et al., 2017; Grizzetti et al., 2016; Ncube et al., 2018).




| Variables | Specific ES provided | ES classification |
|---|---|---|
| | Food | Provisioning |
| | Fibre | Provisioning |
| | Energy | Provisioning |
| | Fuel | Provisioning |
| | Spiritual, religious, inspirational & sense of place | Cultural |
| | Recreation, tourism & aesthetic appeal | Cultural |
| | Social relations | Cultural |
| | Educational | Cultural |
| | Cultural heritage & sense of place | Cultural |
| | Medicine & genetic resources | Provisioning |
| | Disease and health | Regulating |
| | Soil formation & quality | Supporting |
| | ***Nutrient cycling & primary production*** | ***Supporting*** |
| | Energy and carbon transfer | Supporting |
| | Habitat & biodiversity | Provisioning |
| | Photosynthesis and evapotranspiration | Supporting |
| | Water supply (domestic, commercial, industrial, agricultural & energy) | Provisioning |
| | Building materials | Provisioning |
| | Biochemical products | Provisioning |
| | Water quality | Support/ Regulate |
| | Water cycle regulation | Support/ Regulate |
| | Pollination | Supporting |
| | Climate regulation & air quality | Support/ Regulate |
| | Landscape formations | Supporting |
| | Flood protection | Provisioning |
| | ***Flood regulation*** | ***Regulating*** |
| | Erosion protection | Provisioning |

Figure 2.5 Conceptual connectivity between NFM multiple benefits and ecosystem services (ES) in relation to riparian buffer strips with variable categories that can be considered for monitoring. This framework is used to determine the most effective monitoring strategy for this research to enable effective monitoring of multiple ES. Adapted from McLean et al. (2013).

A recent synthesis of ES research and implementation (Costanza et al., 2017) highlights the concept of the ES cascade whereby services lead to benefits which concludes with a valuation. Costanza et al. (2017) dispute this concept as being biased towards tangible ES whereas the indirect ES (e.g. supporting services) that crucially underpin those tangible ES are excluded from valuation. The authors emphasise the importance of accounting for supporting ES and that often they are used as proxies to other ES that either cannot be easily quantified or may be more resource intensive (Costanza et al., 2017).

This thesis is focused on NFM but uses a subset of ES to exemplify how the ES approach could be utilised to assess NFM multiple benefits. Algae biomass is utilised as an indicator of ecological quality conditions, which in turn relate to supporting ES (Figure 1.1, page 4), but this study also outlines a framework of how algae biomass links to multiple ES. Nutrient cycling and primary production are crucial supporting ES which underpin multiple ES. Algae biomass has an integral role in nutrient cycling and primary production, and hence algae biomass is used as an indicator of these supporting ES.

### *2.5.1 Supporting ecosystem services*

Primary production is the conversion of solar energy into chemical energy whereby photosynthesising organisms (i.e. algae) utilise sunlight to transform inorganic carbon into organic matter (Bott, 2007). All algae are primary producers and are a fundamental food resource to higher trophic levels of a riverine ecosystem. Primary production is considered a supporting ES (Yeakley et al., 2016) as it provides no tangible benefit to humans but is a critical ecosystem function which sustains food webs and cycles nutrients. Ultimately, primary production affects more perceptible benefits such as healthy fish populations and improved water quality (which reduces the added expense of cleansing prior to supply of drinking water). A further supporting ES is nutrient cycling, which primarily relates to carbon, nitrogen and phosphorus. As stated, algae convert inorganic carbon (e.g. carbon dioxide in the atmosphere) into organic biomass and when the algae die off or are consumed by other organisms (which also ultimately die off), the carbon begins its cycle again when the carbon in these organisms mineralise (Bunn et al., 1999). Nitrogen cycling in the freshwater environment is *fixation* of nitrogen gas from the atmosphere and the conversion of this atmospheric nitrogen as well as organic nitrogen into ammonia by *ammonification* in algae bacteria (Tank et al., 2017). Microorganisms (including algae) also perform *nitrification* and *denitrification* which transforms ammonia into nitrites and nitrates, respectively.

### *2.5.2 Regulating ecosystem services*

The role of algae in climate regulation has been highlighted by the vital role algae have in the carbon and nitrogen cycle. Algae are essentially a sink and a source of carbon dioxide and dinitrogen gas in the atmosphere, which are linked to climate change and atmospheric warming (Houghton, 2009).

Limiting the risk of eutrophication also limits the impact excessive algae growth can have on climate regulation.

Flood regulation has benefits to societal well-being (Millennium Ecosystem Assessment, 2005), especially where communities are situated on natural floodplains. According to Stürck et al. (2014), flood regulation is an ecosystem's capacity to reduce flood hazard, frequency, magnitude and duration. This is achieved by a catchment's ability to reduce and slow runoff generated during precipitation events (Stürck et al., 2014). The delivery of flood regulation ES in a catchment depends on the topography, land use, soils, climate and location of communities. There are interlinkages with the concept of NFM whereby natural features and processes in a catchment are utilised to slow, store and reduce runoff (Section 2.1.1). Reduction is runoff is fundamental to flood regulation. This thesis aims to ascertain the influence of riparian buffer strips on the attenuation of runoff at field scale and at catchment scale. At field scale, overland flow is measured as 'runoff' whereas as catchment scale river discharge is a measurement of cumulative catchment runoff on the river network.

## 2.6 Algae as an ecosystem indicator and the services underpinned by their processes

Algae in any water environment are crucial to the supporting ES due to the fundamental role they have in nutrient cycling and primary production. Algae are highly sensitive to environmental conditions (Figure 2.6) and easy to sample, hence being widely used as an environmental indicator (Environment Agency, 2016; Royer et al., 2008; Wu et al., 2017). Algae provide more than a snapshot of environmental conditions (e.g. water samples indicate conditions only at time of sampling) as they assimilate and respond to conditions over a longer period of time (Figure 2.6), providing an improved indication of prevalent conditions (Bennett et al., 2017). Snell et al. (2014) for example, highlighted algae (diatoms) were able to indicate the flow conditions for the previous 15 -21 days and the Total Phosphorus conditions for the previous 7 -21 days.

The biomass of algae is affected by light (Warren et al., 2017) temperature (Royer et al., 2008), flow conditions (Hutchins et al., 2010; Wu et al., 2017), nutrient inputs (Choi et al., 2015) and contamination from heavy metals (Pavlović et al., 2016). These influences are highlighted in Figure 2.6. In rivers, there are two types of macroalgae: benthic (attached to the river bed, also referred to as *periphyton algae*) and sestonic (suspended in the water column, also referred to as *pelagic algae* or *phytoplankton*) (Wu et al., 2017). Too much algae can lead to eutrophication and concern is growing for freshwaters where eutrophication is becoming an increasing problem (Environment Agency, 2016). Eutrophication is a result of over-enrichment of nitrogen and phosphorous, which causes excessive growth of algae and in turn, depletes dissolved oxygen levels (Withers et al., 2014). Excessive benthic algal growth degrades habitat availability for macroinvertebrates and excessive sestonic algae generation creates turbid conditions and limits light (Figure 2.6) to macrophytes (Environment Agency, 2016). These algal 'blooms' intensify primary production and the consequential hypoxic conditions can result in the loss of fish populations. Reduced dissolved oxygen, caused by an increase in bacterial consumption of organic matter and respiration, propagates hypoxic conditions and is stimulated by excessive algae growth (Correll, 1998). Hypoxic conditions are especially prevalent at night, during low flows, in warmer temperatures, and when phosphorus (the most responsive nutrient) is in excess (Correll, 1998). The economic consequences of eutrophication include increased costs for water treatment (for drinking), loss of biodiversity, devalued house prices and tourism decline (Withers et al., 2014), estimated to cost the UK approximately £75–114 million per year (Pretty et al., 2003). The escalation of freshwater eutrophication concern poses a serious challenge for managing the water environment to mitigate future impacts on economic costs, environmental degradation and societal well-being. Managing water quality, water resource and flood risk are part of the same hydrological nexus linked by weather, land use and soils. Hence, an integrated management approach, like the ES approach, is required for the most effective inclusive management regimes to be implemented.

Algal biomass is measured by utilising chlorophyll-a (Chl-a) concentrations as a proxy and is standard practice in the UK (WFD-UKTAG, 2014). The measurement of algae biomass using Chl-a concentration is used in this study as a proxy to ecological quality to adhere to national standards. Böck et al. (2018) outline the considerations for selecting an ecosystem indicator:

- The indictor should either be a component of the environmental condition being assessed, be representative of the environmental condition being assessed, or be able to reflect environmental changes.
- Practicality of an indicator should be considered or the use of existing data.
- The ability to compare to indicator results to other studies.

Using the above three approaches of Böck et al. (2018) and considering the practicality of resource availability to minimise laboratory costs, sestonic algae biomass was assessed in the research for this thesis using an algae torch to enable rapid in-field measurements. Some researchers argue sestonic algae is not a good indicator in lotic systems (Chambers et al., 2012; Morgan et al., 2006; Royer et al., 2008) due to the influence of shading and short residence time during high flows. Despite questioning sestonic algae as an indicator Royer et al. (2008) recommended it as an indicator in larger rivers. Several other studies (Choi et al., 2015; Environment Agency, 2016; Wu et al., 2017) have supported the use of sestonic algae as an indicator of ecological quality due to their inherent response to various environmental conditions illustrated in Figure 2.6.

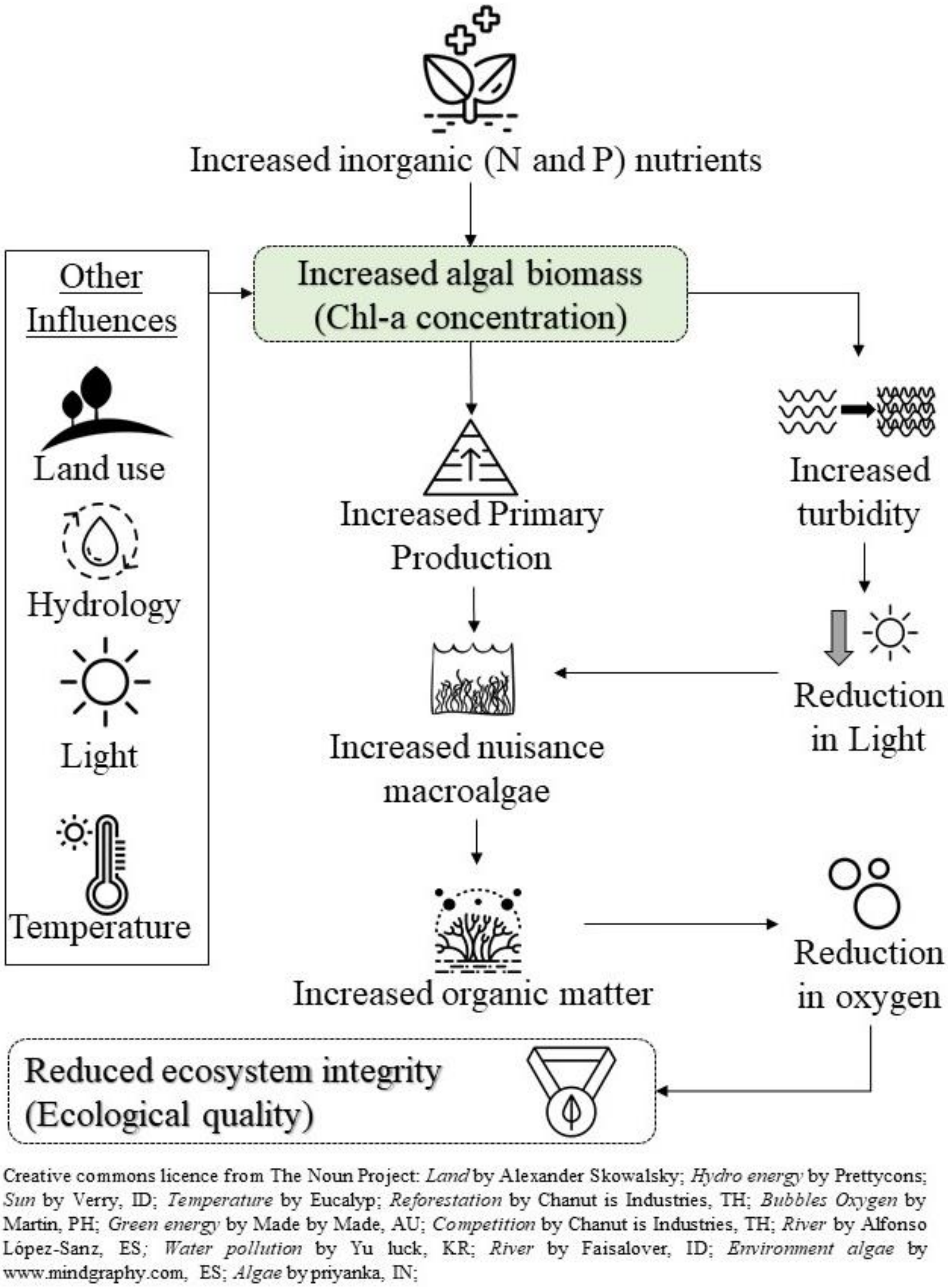



Figure 2.6 Conceptual illustration of algae biomass and the interplay of influences, algae biomass response and consequential outcomes. Algae are critical in nutrient cycling and in turn being effective primary producers, which are supporting ecosystem services. Adapted from Royer et al. (2008).

### *2.6.1 Sestonic algae and ecosystem services*

Ecological studies of lotic algae functions are complex therefore this study will aim to synthesis and generalise literature to establish the functions of sestonic algae and how they may relate to wider ES.

Seston are made up of biotic (e.g. algae and bacteria) and abiotic (e.g. sediment and detritus) fine particulate material floating in the water column and are a vital food source for (macroinvertebrates) filter-feeders (Wallace et al., 2007). Sestonic algae are transported in the longitudinal continuum of river systems or consumed by filter-feeders in the process (Wallace et al., 2007). In upland streams, residence time often exceeds the plankton generation time meaning their concentration is more abundant in slower moving lowland rivers (Carvalho et al., 2002). Nevertheless, phytoplankton biomass and the proxy indicator, Chl-a, represent an assimilatory ecological response to all influencing factors including: nutrients (nitrogen or phosphorus), light, temperature and flow conditions (Carvalho et al., 2002). Upstream phytoplankton concentrations may well be lower than downstream concentrations but can indicate the prevalent site conditions and the contribution to downstream loads of phytoplankton. Excessive growth of phytoplankton (and other algae) and their impact on drinking water, fish populations and ecosystem functions has raised concern for the influence of diffuse nutrient enrichment and eutrophication of rivers (Newman et al., 2005). However, due to the differences in phytoplankton abundance that are unique to a location's stream order, flow rates, nutrient inputs, light and temperature, a uniform monitoring methodology has remained absent in Europe (Carvalho et al., 2002).

Yeakley et al. (2016) highlight the challenge of managing the complexity of lotic ecosystems by ensuring the vital functionality of supporting and regulating services are maintained but also deliver provisioning and cultural ES. The functionality of these ES has the added complexity of spatial scales and unique conditions of each location (e.g. geology, soils, topography, climate and stream order) (Yeakley et al., 2016).

## 2.7 Influence of riparian buffer strips on algae

Riparian buffer zones can consist of various vegetations types including trees, shrubs and grasses, or a mixture of these. Depending on the size of the river and the height of the vegetation, riparian buffer strips can provide shading and in turn, reduce water temperatures. Algae biomass growth is enhanced with increased temperatures and light exposure (Royer et al., 2008; Warren et al., 2017) and riparian vegetation shading is advocated as an algae (and eutrophication) management measure (Hutchins et al., 2010).

As mentioned previously, riparian buffer strips were originally implemented to address water quality issues and filter diffuse nutrient runoff from land uses. By limiting the nutrient inputs in which algae thrive on for generation as well as limiting light penetration and water temperatures, riparian buffer strips can limit the unnecessary growth of algae (Stutter et al., 2012; Warren et al., 2017; Wu et al., 2017). These riparian functions essentially disrupt prime nutrient and abiotic conditions for excessive algae biomass.

## 2.8 Summary of research gaps

Research gaps identified include the following:

*NFM in general:*

- Timeframes of effectiveness are uncertain due to the time required for vegetative measures to become established.

- The impact of NFM measures quantified at local scale does not translate to catchment scale in terms of decrease or delay of peak flows.
- It is uncertain whether NFM measures can synchronise flood peaks of sub-catchment tributaries and enhance flood risk further downstream.
- Effectiveness of NFM measures at reducing and delaying peak flows at higher return periods is uncertain, especially with increasing spatial scale.
- Studies on the impact of

*Riparian buffer strips as an NFM measure:*

- There is a lack of understanding of the role of riparian buffer strips in mitigating flood risk and whether they should be considered an NFM measure.
- Bias toward disciplines other than hydrology has resulted in a lack of evidence of the ability of riparian buffer strips to attenuate surface runoff in relation to FRM.
- Climate change could lead to riparian buffer strips being overwhelmed during intense and/or prolonged rainfall events.
- Concentrated flow paths through riparian buffer strips may limit attenuation effectiveness.
- Despite the plethora of literature on optimal buffer strip widths, there is a distinct lack of consensus and they continue to be implemented uniformly with no regard for localised conditions.
- Studies assume riparian buffer strips should be implemented on floodplain zones to attenuate out of bank flows. Limited studies consider their attenuation and effectiveness when implemented in upper catchment hillslopes.

*Agricultural land management surface runoff:*

- The impact of bare soil increased runoff generation is evidence at local scale but impacts at catchment scale have yet to become evident.
- There is limited evidence that minimum tillage practices reduce surface runoff.
- The impact of concentrated flows of surface runoff (formed due to microtopography) on whether riparian buffer strips receive overland flow is relatively unknown.

*Modelling:*

- In terms of modelling the impact of riparian buffer strips on flood risk at catchment scale, work for this thesis was identified as the only research in a UK context. Studies are lacking.

*ES and algae:*

- There are multiple classifications of ES and a global consensus is required.
- There is a lack of a unified methodology in which to implement an ES approach.
- Sestonic algae are disputed as to whether they are an adequate indicator of ecological quality in rivers.

# Chapter 3 Experimental methodology

## 3.1 Introduction

A lack of understanding of how riparian buffer strips mitigate flood risk was identified in Chapter 2. This deficiency in research especially applies to upland areas where riparian buffer strips are located on hillslopes. Understanding the effectiveness of riparian buffer strips at intercepting and attenuating runoff will address a research gap in determining whether buffers can be considered an NFM measure. Provision of multiple ES is a necessity of NFM measures and a simultaneous quantification of multiple ES (inclusive of flood regulation) provided by riparian buffer strips are lacking. Supporting ES such as nutrient cycling and primary production, are fundamental to other ES and the overall condition of these ES can be indicated using algae biomass. Although flood regulation is also considered at catchment scale (Chapter 4 and Chapter 6), the methodology in this chapter applies to field scale and multiple ES (flood regulation, nutrient cycling and primary production) as illustrated by Figure 1.1 (page 4). This chapter sets out the methodology and analysis undertaken for RQ1 and RQ2 (RQ3 methodology is outlined in Chapter 4). There are three main areas of research in this study:

- Field based surface runoff experiment:
    - RQ1: What are the different conditions by which overland flow moves into and through riparian buffer strips?
- Field based algae ES experiment:
    - RQ2: What is the impact of riparian buffer strips on algae concentrations in streams as an indicator ecological quality and ecosystem services?
- Hydrological modelling of catchment wide riparian buffer strips (addressed in Chapter 4)
    - RQ3: How effective are catchment-wide riparian buffer strips at reducing peak flow and what is the most effective riparian buffer strip width and vegetation type (using SWAT model as a tool)?

To address RQ1, a rationale of variable selection dictated the design of the surface runoff experiment within a riparian buffer strip (also referred to as buffer strip throughout this study) and is outlined in the methods. The experimental design and setup are detailed and followed by an outline of how study variables are defined and calculated. Data analysis undertaken to address RQ1 is explained.

The algae ES experiment design is outlined in a similar manner to the surface runoff experiment. Experiment locations are presented and explained in relation to RQ2. The experimental setup is then illustrated and followed by details of analysis that will address RQ2.

## 3.2 Case study catchment

The study site is situated within the Tarland sub-catchment of the River Dee in North East Scotland. The Tarland Burn is approximately 17 km in length and flows in a North West to South East direction through Tarland village and Aboyne before its confluence with the River Dee. It has a drainage area of 73 $km^2$ and is dominated by a range of intense agriculture (rough grassland, pasture and arable) and forestry (Figure 3.1).

The Tarland catchment has flooding and water quality issues which are monitored by a variety of means. The Tarland catchment has experienced flooding in Tarland village, Aboyne and to agricultural land to some extent in: April 2000, October 2002, June 2005, December 2005, March 2006, February 2006, July 2009, December 2009, December 2015, and January 2016 (SEPA, 2016b). Tarland catchment is designated as a potentially vulnerable area (PVA) by Scottish Environment Protection Agency (SEPA), which earmarks the catchment as requiring actions to address the flood risk (SEPA, 2015). Monthly water quality testing is undertaken across the catchment by JHI and there are river gauging stations at Netherton, Tarland village, Coull, and Aboyne (Figure 3.2). A weather station is located near Aboyne; and there is a rain gauge located at Davoch (Figure 3.2)

The Tarland catchment has been a key focus for water management issues in terms of water quality and NFM. Figure 3.3 illustrates a timeline of projects undertaken in the Tarland catchment as part of integrated catchment management and highlights the existing management measures: riparian buffer strips, wetland and temporary storage ponds. Tarland has also been identified by SEPA as a pilot catchment project area by having a *high potential benefit* for NFM implementation (SEPA, 2018). A community wetland in Tarland village and an offline flood storage wetland at Mill of Gellan was completed in conjunction with the AQUARIUS Interreg IVB North Sea Region Programme and the EU REFRESH project, which focused on flood risk, water quality and land management. Riparian buffer strips were implemented from the late 1990s to 2009 at various locations along tributaries, mostly in the upper parts of the catchment, to address water quality issues (Figure 3.3). An estimated 0.1 $km^2$ of riparian buffer strips are known to have been implemented, mostly in 2005 and 2009-2010.

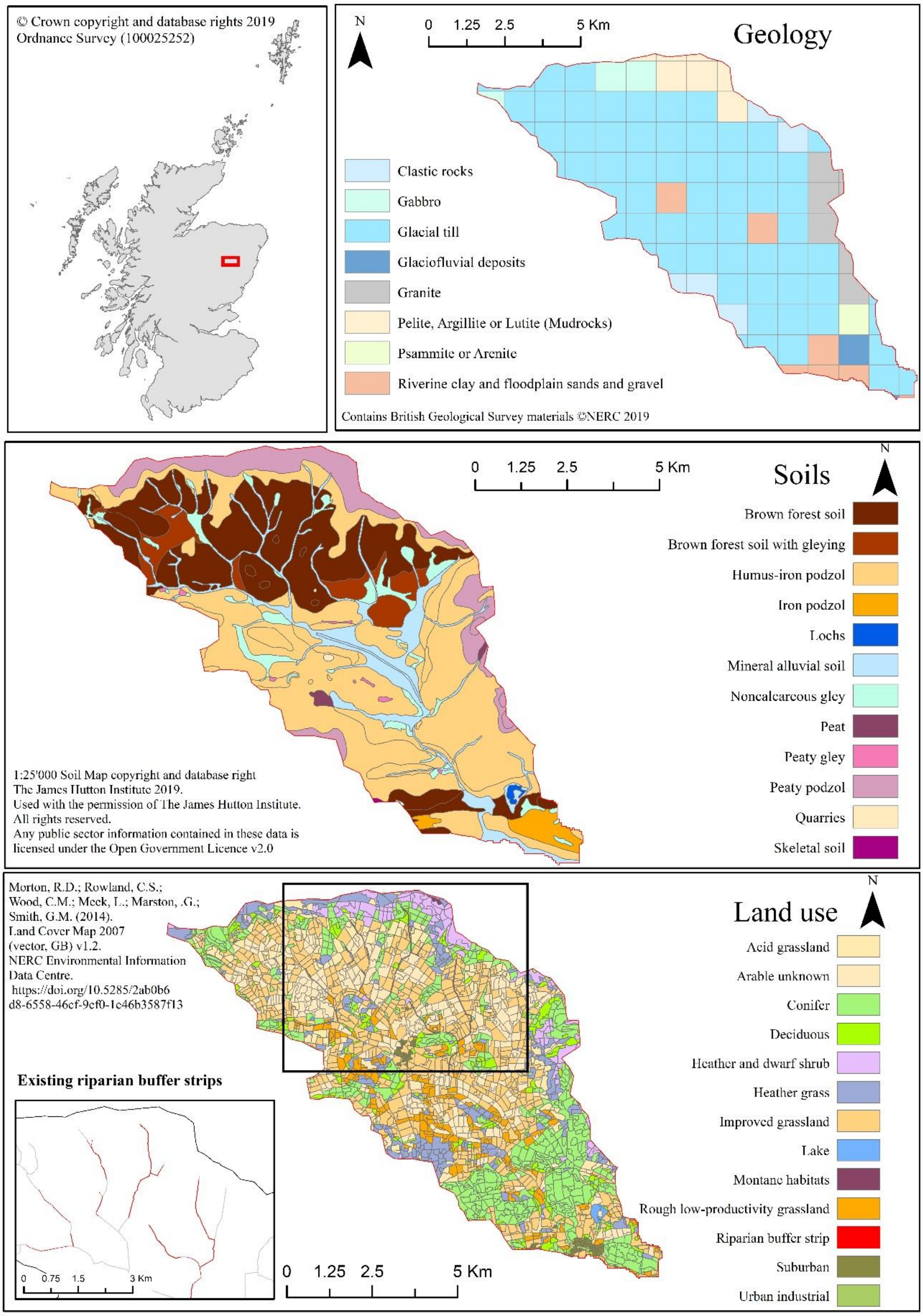



Figure 3.1 The distribution of catchment geology, soils, land use and existing riparian buffer strips in Tarland catchment.

The catchment is primarily underlain with glacial till, with riverine clay and floodplain sands and gravels in low-lying land. The upper region in the North consists of mudrocks and gabbro rock, and the upper eastern region consists of granite (Figure 3.1). Peat-based soils overlay the igneous rocks (gabbro and granite) and mudrocks in the upper north and east of the catchment. The upper catchment is primarily brown forest soil and the middle to lower catchment is mostly humus-iron podzol. Mineral alluvial soils are shown to follow the river network (Figure 3.1).

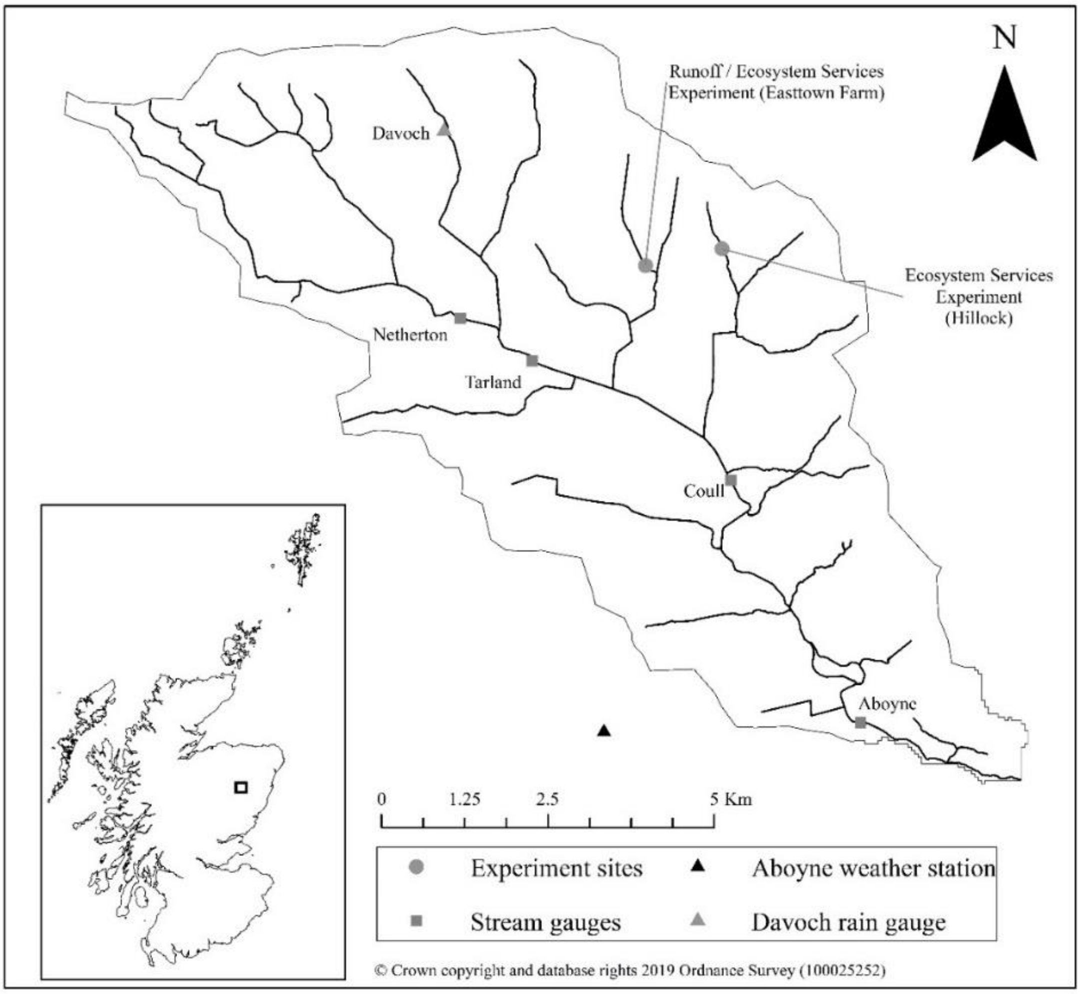



Figure 3.2 Tarland gauging stations and experiment sites.


Figure 3.3 Timeline of projects in Tarland catchment as part of an integrated catchment management approach.

The Tarland sub-catchment of the River Dee in North East Scotland was selected for this study due to several factors:

- The existing (and well documented) network of riparian buffer strips were implemented from approximately the mid-1990s to 2009 in upper parts of the catchment (primarily to manage water quality issues associated with agricultural diffuse pollution).
- A desire from the estate landowner to utilise NFM measures.
- Extensive landowner engagement about NFM was well established therefore landowner cooperation for implementing an experiment was more likely.

- Tarland was identified by SEPA as a pilot catchment project for having the potential for further NFM implementation (Cbec engineering and Walking-the-talk, 2013).
- Tarland has been designated as a PVA by SEPA due to flood risk (SEPA, 2015).
- Tarland is a data rich catchment, with historical and current datasets (e.g. weather and river discharge), as well as comprehensive spatial datasets (e.g. land use, soils, Light Detection and Ranging (LiDAR) Digital Terrain Model (DTM) (useful for the model build, see Chapter 4) and monthly water quality data (beneficial to the ES analysis). This is a rare example of a data rich catchment.
- The dominant land uses are agriculture and forestry; both types of land use have adopted riparian buffer strips.
- Support from the Dee catchment partnership

Within Tarland catchment, two main sites were used for experiments and data collection: Easttown Farm (runoff and ES experiment) and Hillock (ES only experiment) (Figure 3.2). More details on the experiment site selection are explained in Section 3.2.2 and 3.4.1.

### *3.2.1 Existing datasets*

Existing datasets were obtained to further the analysis of field-based data by assessing hydrological conditions and using spatial datasets to assess the experimental sites (Figure 3.2). Datasets included weather, river discharge and water quality data (Table 3.1), some of which were used in conjunction with the spatial datasets to build the hydrological model (more details provided in Chapter 4). The accuracy of these datasets is defined in Table 3.1 and locations identified in Figure 3.2. Further details on water quality data is provided in Section 3.4.2).

Spatial datasets (Figure 3.1) included the Land Cover Map 2007 (Morton et al., 2014); the National Soils Map for Scotland 2013 (The James Hutton Institute, 2013); a shapefile of existing riparian buffer strips in Tarland provided by JHI; and LiDAR data was also provided by Aberdeenshire Council (via JHI) as a 1 m resolution DTM. The DTM was used to define the catchment area of the surface runoff experiment site. Existing datasets were collated for modelling and experimental analysis. Discharge, rainfall, temperature and water quality data are used in the experimental runoff experiment and the algae ES experiment. Accuracy for discharge states the highest flow and date of occurrence, and the period of the dataset (Table 3.1).

Table 3.1. Outline of variables for existing datasets including their location, source, time-step, unit and degree of accuracy. MIDAS data was supplied by the Met Office (2017a) and CFSR data obtained from National Centres for Environmental Prediction (2016).

| *Variable* | *Location* | *Source* | *Timestep* | *Unit* | *Accuracy* |
|---|---|---|---|---|---|
| Rainfall | Davoch | JHI | 15 minutes | mm | Unknown |
| Rainfall | Aboyne | MIDAS – Met Office (CEDA web processing service) | Hourly and daily | mm | 0.05 |
| Temperature | Aboyne | MIDAS | Hourly and daily | Maximum and minimum degrees Celsius (C) | ±0.1°C |
| Relative Humidity | Aboyne | MIDAS | Hourly and daily | Percentage (%) converted to fraction | ±0.2°C |
| Wind speed | Aboyne | MIDAS | Hourly and daily | Knots (converted to daily average m/s) | ±1 knot |
| Solar radiation | Aboyne | Climate Forecast System Reanalysis (CFSR) | Daily | Daily total solar radiation (Mj/m2) | Unknown |
| Relative Humidity | Aboyne | CFSR | Daily | Daily average relative humidity as a fraction | Unknown |
| Discharge | Aboyne | SEPA (2003-2012) & *JHI (2012-2016) | Hourly and daily | $m^3/s$ | Jul 2003 - Dec 2016 12.34m3/s (04/01/16) |
| Discharge | Coull | | Hourly and daily | $m^3/s$ | Jan 1999-Jan 2016 37.04m3/s (08/01/16) |
| Discharge | Netherton | | Hourly and daily | $m^3/s$ | Jan – Dec 2014 3.98m3/s (14/11/14) |
| Water quality (nutrients) | Runoff experiment site | *The James Hutton Institute (JHI) | Monthly | µg/l or mg/l depending on what is being measured | Unknown |

### *3.2.2 Experimental locations*

The surface runoff experiment site (Easttown Farm) has an established 13-year-old and 9m wide fenced riparian buffer strip. It is 1.5 km long on a first order stream at an elevation of 194 mAOD. The ES only experiment site has no riparian buffer strip. Easttown Farm was selected because it was accessible, located on a hillslope with surrounding agricultural land, and the vegetation was well established. The location of the runoff experiment (Figure 3.2) was chosen based on the following:

- The site is easily accessible with landowner access permissions from the MacRobert's Trust.
- The buffer strip is situated on a hillslope of 8° (average slope) defined by the Scottish Soils Classification as a *strong slope* (The Macaulay Institute for Soil Research, 1984).
- The area draining to the riparian buffer strip is estimated to be 0.33 $km^2$ and consists mostly of rotational arable land which is a popular land use in the catchment.
- The proximity to a secondary site (Hillock; see Figure 3.2) with similar land use (arable and pasture), altitude and slope. The secondary site does not have a riparian buffer strip and was utilised to compare a buffered and non-buffered site for the ES aspect of this study.

The paired in-stream ES experiment site (Hillock) was selected because it was the closest and most similar tributary. Only one experimental site was selected for the surface runoff experiment due to cost and time factors and therefore a detailed approach at the individual site was adopted.

## 3.3 Research question 1: surface runoff experiment and field scale flood regulation

*RQ1: What are the different conditions by which overland flow moves into and through riparian buffer strips?*

The surface runoff experiment was employed to determine whether overland flow, in reality, passed from the adjacent land into the riparian buffer strip where they both interface. This was to identify whether the riparian buffer strip attenuates surface runoff when it is located on a hillslope. As highlighted in Chapter 2, the term ‘surface runoff’ refers to infiltration excess *and* saturation excess overland flow (illustrated in Figure 2.1, page 12). The experimental results (Chapter 5) will define when surface runoff is occurring as infiltration excess or saturation excess (methodology for this is outlined in Section 3.3.2, *Soil infiltration*).

This section outlines the experimental setup, variable selection and estimations of these variables later used for analysis. These include: precipitation, antecedent conditions, land management changes, overland flow type, and derivation of infiltration or runoff events at the experiment site. This section concludes with an outline of analyses conducted to ascertain event conditions and land management conditions during runoff events, and uncertainties in the data.

### *3.3.1 Variable selection*

Background research was conducted to ascertain the multitude of variables that could be monitored to assess the potential multiple benefits of riparian buffer strips. This literature search highlighted potential variables that can be measured in the field. Prior to conducting the literature search, categories of multiple benefits were determined to enable measurable variables to be grouped and subsequently linked to ES. The results of this are illustrated in more detail in McLean et al. (2013) and Figure 2.5 (page 29; full paper in Appendix 1) and were fundamental in designing the surface runoff experiment in a riparian buffer strip. The variables relating to the group “hydraulics/hydrology” are outlined in Table 3.2 and these all relate to flood regulation ES.

Table 3.2. Hydrological benefits of riparian buffer strips and the measurable variables extract from McLean et al. (2013). These relate to flood regulation and water cycle regulation, which are regulating ecosystem services.

| *Category* | *Specific Riparian Benefits* | *Variables* | |
|---|---|---|---|
| Hydraulics/Hydrology (Regulating ecosystem services: flood regulation and water cycle) | Hydrological functions: interception, stem flow, infiltration, evapotranspiration, water storage and floodplain connection<br><br>Hydraulic roughness, turbulence, flood peak reduction | - Canopy density<br>- Species physiology<br>- Vol. rainfall/time<br>- Evapotranspiration rates<br>- **<u>Rainfall/runoff</u>**<br>- **<u>Soil moisture</u>**<br>- **<u>Slope (channel and hill)</u>**<br>- Geology<br>- Temp. (soil, water, air)<br>- Particle size distribution of sediment load (bed and suspended)<br>- Root system<br>- Distance from stream<br>- **<u>Soil infiltration rate</u>**/ compaction | - Soil structure, type and distribution<br>- Vol. of biomass<br>- **<u>Groundwater level</u>**<br>- Time to peak<br>- Base flow<br>- **<u>Stream level/stage</u>**<br>- Peak/stage/bank full discharge<br>- Manning's *n* coefficient<br>- Channel geometry<br>- Overbank area wetted by flood<br>- **<u>Land use</u>**<br>- Stocking densities<br>- Crop species, **<u>cultivation practices</u>** and timeframes |

The variables selected (bold and underlined in Table 3.2) to monitor/measure were: surface runoff; slope; land use change; soil infiltration rates (in the managed adjacent field and in the riparian buffer strip); soil moisture; water table height; and stream water level. With reference to RQ1, it would establish whether rotational land management influenced the overland flow entering the riparian buffer strip. Therefore, it was essential to measure surface runoff, determine the slope and monitor land management changes in the adjacent field. However, soil moisture and water table height were additional variables measured with the intention to establish if the near surface soil became saturated and assist in event identification whereby if the soil moisture responded (indicative of infiltration) but if no runoff was recorded, this was determined as an *infiltration event* (see Section 3.3.5). Stream stage would indicate whether it was influencing the water table or soil moisture in the riparian buffer strip depending on depth, as well as capture full catchment dynamics (e.g. the response from surface, subsurface and base flows).

### *3.3.2 Experimental setup and implementation*

Surface runoff was monitored inside the riparian buffer strip (INRIP) and at the field-buffer boundary (OUTRIP). It was anticipated this would provide empirical field data to address RQ1 by capturing rainfall events that resulted in surface runoff passing over the field-buffer boundary into the riparian buffer strip. The monitored surface runoff INRIP would demonstrate whether surface runoff from these rainfall events continued to pass through the riparian buffer strip, which would provide more hydraulic roughness and therefore attenuation to surface runoff.

A five metre long concrete 'V' shaped channel (V-flume) was installed in a downslope direction, parallel with the adjacent sloping field and stream (Figure 3.4 and Figure 3.5). The flumes were designed using the Modified Rational Method for a 100-year flood event (Institute of Hydrology, 1999) to intercept and capture any surface runoff generated upslope (contributing catchment area of 0.33 km$^2$):

$$Q_p = 2.78\ (C_v\, C_i\ i\ A)$$

Equation 3.1

Where: $Q_p$ is the peak runoff rate (m$^3$/s); $C_v$ is the volumetric runoff coefficient; $C_i$ is the routing coefficient; $i$ is the average rainfall intensity for a duration equal to the time of concentration (mm/hr); and $A$ is the catchment area (ha).

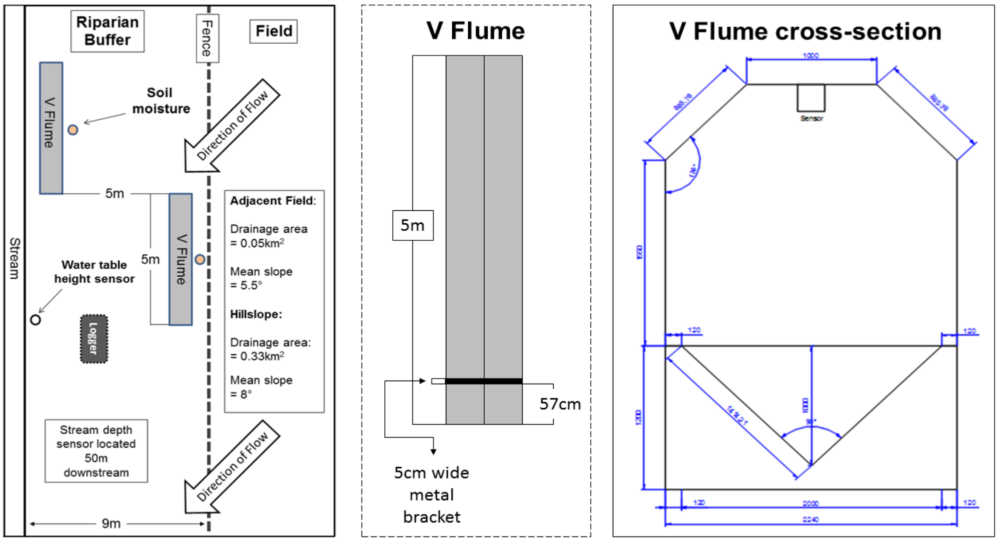



Figure 3.4 Surface runoff experiment setup and flume design. *Left diagram:* bird's eye view of experiment setup with arrows illustrating the general direction of overland flow and location of V-flumes and soil moisture probes. *Middle diagram:* bird's eye view schematic of V-flume design. *Right diagram*: cross-section dimensions of V-flume and the bracket securing the sonic sensor above the flume.

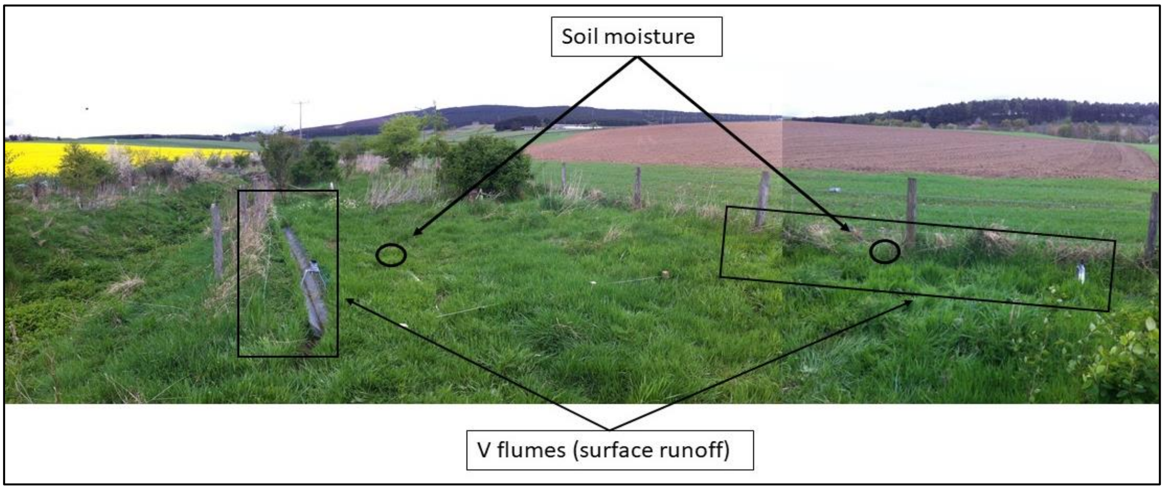



Figure 3.5 Photographic demonstration of experimental setup with arrows signifying the position of the V-flume inside the riparian buffer strip and the V-flume at the edge of the riparian buffer strip and the adjacent agricultural field.

These V-flumes were excavated into the soil with the tips of the ‘V’ flush with the soil surface to allow surface runoff to flow into the flume. An ultrasonic distance measurement sensor situated on a bracket above the V-flume (Figure 3.4 and Figure 3.5) which would measure the height of the water in the V-flume and allow runoff volumes to be calculated. The V-flumes were staggered in their placement due to the directional slope of the land: this mitigated the OUTRIP V-flume closest to the field intercepting overland flow, which may flow through the buffer and be captured by the flume INRIP; a crucial element to answering RQ1. The sensors were calibrated twice in the field and a calibration factor applied to ensure accuracy (Equation 3.2 and 3.3). The calibration factor was determined by using metal plates to sit across the flume at depths of 10 mm, 20 mm, 30 mm, 40 mm, and 50 mm. The lab demonstration is of this field calibration exercise as shown in Figure 3.6.

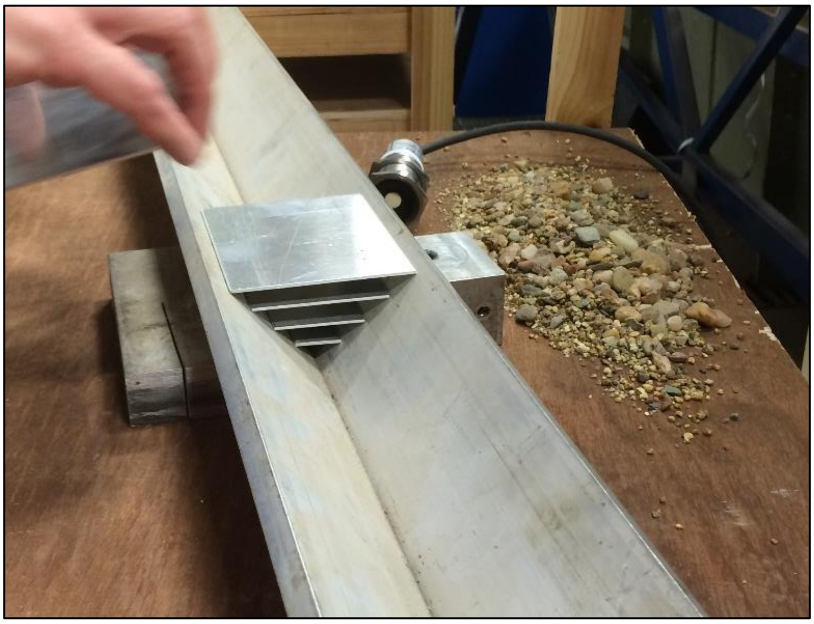


Figure 3.6. Lab test of field calibration of flume depths being represented by depth panels to reflect different water heights.

The live recorded values when these depth plates were applied in the field were then plotted against the plate depths and derived the calibration factor for INRIP and OUTRIP flumes which were applied to all V-flume depth data collected:

$$y = 0.9634x - 280.23$$

Equation 3.2 (INRIP)

$$y = 0.9377x - 268.46$$

Equation 3.3 (OUTRIP)

Where: $y$ is the depth of water in the V-flume (mm); and $x$ is the value output from the sonic sensors.

Runoff depths in the V-flume, stage h (m), were converted to discharge Q ($m^3$/s) estimates using the Kindsvater-Shen V-notch weir formula depicted by BS 368: Part 4 A: 1981 (British Standards Institution, 2008):

$$Q = C_e \frac{8}{15} tan \frac{\alpha}{2} \sqrt{2g_n} h^{5/2}$$

Equation 3.4

Where: $C_e$ is the coefficient of discharge (0.58); $g_n$ is the acceleration due to gravity (m/s); $h$ is the head measurement (m); and α is the angle of the notch (90º). Q was then converted from $m^3$/s to ml/s as flows were too small.

**Soil moisture**

Volumetric water content (VWC) of soil was measured to provide a proxy to infiltration occurring in close proximity to the surface runoff flumes. The VWC was used to analyse the relative change to soil moisture where an increase in VWC indicated infiltration was occurring. The infiltration/VWC data collected would be used to identify rainfall events where no surface runoff was generated, but a response to the rainfall was evident from the soil VWC response (infiltration only event defined in Section 3.3.8). If there was no VWC response, and no surface runoff response, this indicated a likelihood that the rainfall did not fall within the drainage area of the surface runoff experiment (defined as a rejected event, as outlined in Section 3.3.8).

Two MAS-1 soil moisture sensors were used to monitor soil VWC: located approximately in the centre, and 30 cm in front, of the INRIP and OUTRIP flumes and at 20 cm depth (Figure 3.4 and Figure 3.5). Given the location of the sensors in the upper 20 cm of the soil horizon, VWC can be used as a proxy to infiltration (He et al., 2012) and it is assumed that the stream has no influence on soil moisture as the stream bed is 1.3 m below the surface of the riparian buffer strip. The MAS-1 sensors recorded an output current, transformed into VWC using the sensor specific mineral soils calibration equation, with an accuracy of ± 4% VWC (Decagon Devices Inc, 2016):

$$VWC = 0.00328 * mA^2 - 0.0244 * mA - 0.00565$$

Equation 3.5

Where: *VWC* is the decimal percentage volumetric water content; and *mA* is the milliamp output from the sensor. These sensors were calibrated on two occasions using a hand held ML2x Thetaprobe, which have an accuracy of 1% VWC (Eijkelkamp Soil & Water, 1999). Thetaprobe and MAS-1 VWC values were compared to confirm values were within 3% of the MAS-1 value (this would ensure the MAS-1 was within its ± 4% accuracy range as the Thetaprobe has a 1% accuracy). The soil VWC was used to ascertain *relative* change in soil moisture rather than absolute values.

**Soil infiltration**

A single ring open system variable head infiltrometer test was carried out (British Standards Institution, 2012) within the riparian buffer strip (mineral alluvial soil) and in the adjacent arable field (brown forest soil with gleying). It was conducted on a dry day but in moderately wet antecedent conditions to ascertain infiltration rates of the managed arable field and unmanaged riparian buffer strip (Antecedent Precipitation Index (API) for 30 days previous = 51.4 mm; API is explained in Section 3.3.4). These measurements were used to ascertain whether precipitation intensities would result in either infiltration excess overland flow or saturation excess overland flow (as illustrated in Figure 2.1, page 12). If the precipitation intensities were greater than the infiltration rate determined by the single ring infiltrometer, it was assumed overland flow was generated as a result of saturation excess. These results should be used with caution however as single ring infiltrometer tests can be highly variable for example, the same result may be different one metre away from another measurement.

**Water table height**

The purpose of measuring the water table height was to establish rainfall events which: did not occur within the vicinity of the surface runoff experiment, were infiltration only events, or runoff events.

A dip-well was installed approximately 1.5 m from the stream to a depth of 20 cm to measure the height of water table in the hyporheic zone using a pressure transducer. It was situated between the stream and the INRIP flume (Figure 3.4). Achieving a greater depth of dip-well was hindered by rocky material in the alluvial soil of the bank restricting its installation further from the stream and at greater depth. Field calibration by measuring the depth of water in a 1 litre slim beaker at varying depths with the sensor inserted led to the use of a calibration equation:

$$y = 1.0217x - 103.76$$

Equation 3.6

Where: $y$ is the depth of water (mm); and $x$ is the pressure transducer reading.

**Stream level**

The stream water level was also measured to support and inform event classification decisions. Data was used in conjunction with soil moisture and water table height to assist in determining whether rainfall events did occur at the experiment site, especially if there was limited response from soil moisture or the V-flumes. A water level logger (pressure transducer) was installed by JHI on 18$^{th}$ December 2014 at the experiment site to measure stream depth and was installed approximately 25 m downstream from the experiment site at the road culvert.

**Field observations**

To enable analysis of surface runoff events and determine what conditions exist when surface runoff enters the riparian buffer strip (i.e. RQ1), field observations of land use management changes and on-the-ground evidence of flow paths during heavy rainfall events were used. These observations were evidenced by photographs.

In response to field observations during a high flow event, ArcGIS was utilised to determine overland flow paths of the surface runoff experiment area. A 1 m resolution DTM was used in the ArcGIS *flow accumulation* tool to establish where flow paths would occur and determine if they reflected those witnessed in the field. This assessment would enable further discussion (Chapter 7) as to whether this could have been predicted using this approach.

A time-lapse field camera (Bushnell) (Figure 3.7) was installed facing the OUTRIP flume outflow to enable a qualitative secondary backup measurement.

Figure 3.7. Bushnell field camera setup at the OUTRIP flume.

The changes to land use management in the adjacent field and seven upslope fields (on the left bank) from the riparian buffer strip experiment site (Figure 3.8) were captured using photographs from a similar location each month alongside field notes on conditions. All fields are dominated by brown forest soils with some gleyed brown forest soil in the adjacent field, but all fields are arable land (Figure 3.8).

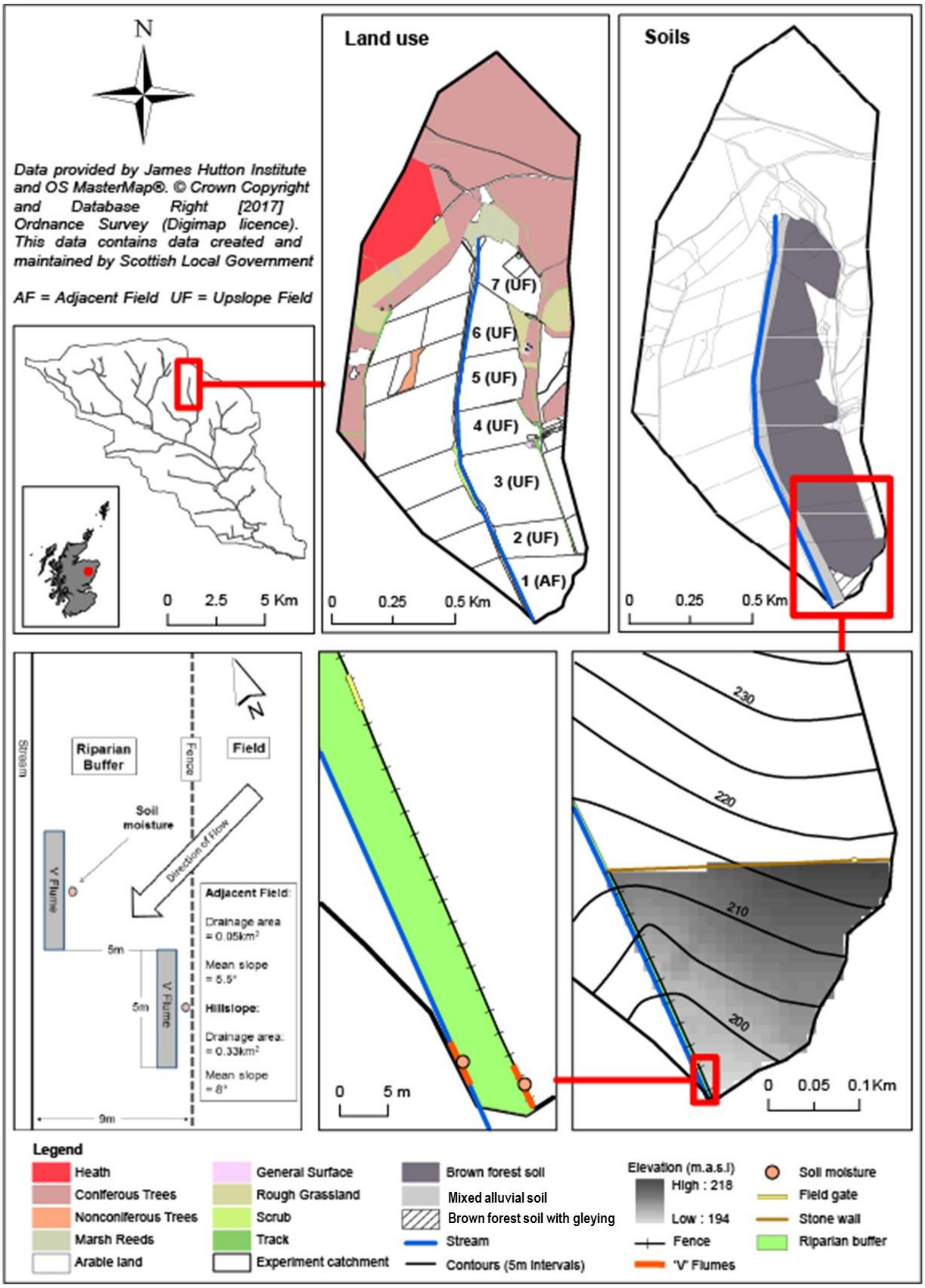



Figure 3.8. Experiment site characteristics and experimental setup. Land use and soils illustrate the spatial distribution of upslope fields (UF) and the adjacent field (AF) to the experiment site. The topography of the AF is shown using contours and a digital terrain model (DTM). The experimental set up is shown from a bird's eye view showing the likely direction of overland flow based on the slope of the land and DTM.

These high-resolution photographs determined the approximate height of crop, type of crops, extent of bare soil, and time periods where distinct changes had taken place. As runoff generation in the adjacent field is more likely to affect overland flow at the V-flume (compared to those further upslope separated by dry-stone walls), two sets of land use categorisation was used: land management activity in the immediately adjacent field to the experiment, and land management activity in adjacent *and* upslope fields. These categories would develop a timeline of land management activities. Within each month period there is uncertainty in relation to the specific day the land use changed as each photograph represents the conditions at the time of capture only. This was addressed by stating that the land use had changed on the day the picture had been taken as this could be evidenced.

**Temporal scales of monitoring**

The period in which the aforementioned variables were measured was from 19 December 2013 to 14 December 2015. Each variable monitored is outlined in Table 3.3 and identifies periods of missing data, as well as data obtained externally to this research but applied to the field site.

Table 3.3. Temporal scales of variables monitored which are relevant to the experimental aspects of this study (RQ1 and RQ2). Missing data periods are identified in red. No recording period represented by grey.

| | | | *15-minute variables* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Year* | *Month* | *Day* | *Davoch Rainfall (existing data)*[1] | *Aboyne Rainfall (existing data)*[2] | *Aboyne Temperature (existing data)*[2] | *Soil moisture (INRIP)*[3] | *Soil moisture (OUTRIP)*[3] | *Surface runoff (INRIP)*[3] | *Surface runoff (OUTRIP)*[3] | *Water table level*[3] | *Stream level*[3] |
| 2013 | Dec | 19 | | | | | | | | | |
| | Jan | 8 | | | | | | | | | |
| | | 29 | | | | | | | | | |
| | | 30 | | | | | | | | | |
| | Feb | 26 | | | | | | | | | |
| | Mar | 4 | | | | | | | | | |
| | | 5 | | | | | | | | | |
| | Apr | | | | | | | | | | |
| | May | | | | | | | | | | |
| | Jun | | | | | | | | | | |
| 2014 | Jul | 20 | | | | | | | | | |
| | Aug | 21 | | | | | | | | | |
| | | 22 | | | | | | | | | |
| | Sep | 16 | | | | | | | | | |
| | Oct | | | | | | | | | | |
| | Nov | 5 | | | | | | | | | |
| | | 6 | | | | | | | | | |
| | | 25 | | | | | | | | | |
| | Dec | 15 | | | | | | | | | |
| | | 16 | | | | | | | | | |
| | Jan | | | | | | | | | | |
| | Feb | | | | | | | | | | |
| | Mar | | | | | | | | | | |
| | Apr | | | | | | | | | | |
| | May | | | | | | | | | | |
| | Jun | 20 | | | | | | | | | |
| | | 21 | | | | | | | | | |
| | | 22 | | | | | | | | | |
| 2015 | | 26 | | | | | | | | | |
| | Jul | 9 | | | | | | | | | |
| | | 10 | | | | | | | | | |
| | Aug | | | | | | | | | | |
| | Sep | | | | | | | | | | |
| | Oct | 22 | | | | | | | | | |
| | | 27 | | | | | | | | | |
| | | 28 | | | | | | | | | |
| | Nov | | | | | | | | | | |
| | Dec | 14 | | | | | | | | | |
| 2016 | Jan | 8 | | | | | | | | | |

| | | *Monthly variables* | | | |
|---|---|---|---|---|---|
| *Year* | *Month* | *Water quality samples*[1] | *Land management photographs*[3] | *Chlorophyll-a & water temperature experiment site (buffered)*[3] | *Chlorophyll-a & water temperature Hillock site (non-buffered)*[3] |
| 2013 | Dec | | | | |
| | Jan | | | | |
| | Feb | | | | |
| | Mar | | | | |
| | Apr | | | | |
| | May | | | | |
| 2014 | Jun | | | | |
| | Jul | | | | |
| | Aug | | | | |
| | Sep | | | | |
| | Oct | | | | |
| | Nov | | | | |
| | Dec | | | | |
| | Jan | | | | |
| | Feb | | | | |
| | Mar | | | | |
| | Apr | | | | |
| | May | | | | |
| 2015 | Jun | | | | |
| | Jul | | | | |
| | Aug | | | | |
| | Sep | | | | |
| | Oct | | | | |
| | Nov | | | | |
| | Dec | | | | |

[1] James Hutton Institute data
[2] Met Office (2016) data
[3] Experimental data for this research

Experimental period for this study is from 19 December 2013 to 14 December 2015.

### *3.3.3 Precipitation scales and analysis*

Precipitation data did not exist for the experiment site and was not monitored as part of the experiment due to increased equipment costs, logger capacity for number of equipment inputs, and existing precipitation data elsewhere in the catchment. This resulted in a trade-off between site specific accuracy of precipitation and recording of other variables (e.g. soil moisture and runoff). Other variables were prioritised to enable further analysis of runoff events (e.g. determine whether infiltration occurred and measuring the stream level) therefore, the existing precipitation data was used.

Tarland catchment has two rain gauges (Davoch (JHI) and Aboyne (Met Office 2016), respectively; see Figure 3.2for location and Table 3.1 for timestep and accuracy). Both rain gauges had available data for the experiment period (December 2013 to January 2016). These two sources of precipitation data differ (temporally and spatially) in the following ways:

- Davoch rain gauge recorded at 15-minute intervals whereas, Aboyne recorded at hourly intervals (Table 3.1);
- Davoch rain gauge is closer to the experiment site (3.6 km$^2$) than Aboyne (7.1 km$^2$) as shown in Figure 3.2;
- Davoch rain gauge and the experiment site are in the upper catchment but Aboyne is in the lower catchment;

Precipitation data from both sites were used to allow Aboyne data to substitute missing periods of Davoch data and to incorporate the accuracy of Aboyne precipitation data (0.05 mm; Table 3.1). Statistics for Davoch and Aboyne precipitation were assessed prior to calculating catchment average precipitation (referred to as catchment precipitation herein) and deemed adequately similar despite differing geographical locations (Table 3.4).

Table 3.4. Precipitation statistics for Davoch and Aboyne rain gauges. Annual Average Rainfall (AAR) statistic for Davoch is derived from data recorded from 14 February 2012 to 16 February 2016. Aboyne AAR is derived from data recorded from 1 January 1994 to 31 December 2015.

| | ***AAR (mm)*** | ***Within 10% of AAR*** | ***Correlation coefficient*** | ***Covariance statistic*** | ***Max (mm)*** | ***Mean (mm)*** | ***Standard Deviation (mm)*** | ***Standard Error (mm)*** |
|---|---|---|---|---|---|---|---|---|
| **Davoch** | 782.45 | Yes | 0.6 | 0.13 | 16.4 | 0.11 | 0.43 | 0.003 |
| **Aboyne** | 812.00 | Yes | | | 14.0 | 0.11 | 0.47 | 0.004 |

Catchment precipitation was calculated using the Thiessen polygon method (Thiessen, 1911). The rain gauge sites are 9.6 km apart, 3.6 km west and 7.1 km south from the experiment site, respectively (see Figure 3.2). ArcGIS *create polygons* function calculated the area attributed to both Davoch and Aboyne gauges and the weight of each polygon was calculated as follows:

$$Wi = \frac{Ai}{At}$$

Equation 3.7

Where: *Wi* is the weight of area for the rain gauge; *Ai* is the polygon area for the rain gauge ($m^2$); and *At* is the total catchment area ($m^2$). These weights were applied by multiplying the rainfall from the respective gauge and summing both values. The catchment rainfall was calculated by:

$$P_c = (Wi_1 \cdot P_1) + (Wi_2 \cdot P_2)$$

Equation 3.8

Where: $P_c$ is catchment rainfall (mm); $P_1$ is Davoch rainfall (mm); and $P_2$ is Aboyne rainfall (mm). Precipitation data was occasionally missing, likely due to logger failure. During periods where there was no precipitation data for either Davoch or Aboyne, the gauge with data was used in its original format. There were no instances where there was no precipitation data for both stations at the same time.

Variables at the experiment site were monitored at 15-minute intervals and time series analysis required the precipitation data to exist at the same timestep. As Aboyne precipitation was hourly and Davoch was in 15-minute intervals, the catchment precipitation was interpolated into 15-minute intervals using weighted values derived from Davoch. An exception being for the autumn and winter periods in which there was no Davoch data (16 September 2014 to 5 November 2014 and 25 November 2014 to 15 December 2014). Here, Aboyne data was averaged over the hour (divided by 4 for 15-minute data): an appropriate alternative as it was assumed there would be limited influence from convective storms as it was the late autumn and winter period. The catchment precipitation was calculated from 19 December 2013 to 14 December 2015 for which corresponding surface runoff and soil VWC data exists.

### *3.3.4 Antecedent precipitation index*

An understanding of the antecedent conditions prior to a rainfall event is an important element in defining the conditions by which surface runoff does or does not occur in the riparian buffer strip. Likewise, it is beneficial to understand the conditions by which infiltration occurs, but surface runoff does not. Antecedent conditions essentially provide an indication of how wet or dry the catchment is prior to a rainfall event. If the catchment is considered to have high antecedent conditions, the surface runoff response is expected to be as saturation excess overland flow where the soil reaches its full capacity to hold water and overland flow is generated. This study used the antecedent precipitation index (API) which uses rainfall data as a substitute for catchment scale soil moisture data. API is a separate entity to the soil moisture data being collected for the experiment and is used to be independent of experimental measurements. API can be calculated for a range of periods preceding the chosen event date. Saxton and Lenz's (1967) definition of API for a single day of rain as follows:

$$API_i = P_k K^t$$

Equation 3.9

Where: $K$ is the reduction factor, $t$ is the time in days, $P$ is precipitation that day (mm) and, $i$ is the selected day (Saxton and Lenz, 1967). If more than one precipitation event occurs within the 30-day period prior to the selected day, daily indexes are calculated (Saxton and Lenz, 1967). The index is calculated by adding the previous day's precipitation before calculating the API for the next day and $t$ now =1. Equation 3.9 then becomes:

$$API_i = (API_{i-1} + P_{i-1})K$$

Equation 3.10

However, the method by Saxton and Lenz (1967) does not account for evapotranspiration and thereby a similar method by Osborne (2009) was used to calculate the API for 30 days prior to the rainfall event:

$$API = \sum_{n=30}^{n=1} [P - E]_n K^{n-0.5}$$

Equation 3.11

Where: $n$ is the number of days before, $P_n$ is the rainfall on the day (mm), $E_n$ is the evaporation on the day (mm/day), $K$ is the decay factor (0.5) and $[P - E]$ is the net rainfall which can not be a negative value (Osborne, 2009). Evaporation is estimated to be 0.1 mm/day in winter, 0.2 mm/day in spring and autumn, and 0.3 mm/day in summer as per industry standard (Osborne, 2009). Decay factors are based on soil index (Institute of Hydrology, 1999). This study used index 2 where $K$ = 0.5 (Osborne, 2009).

### *3.3.5 Event identification*

Identifying rainfall events from catchment precipitation data was the first step in narrowing the focus of time periods where there may have been surface runoff flowing through the riparian buffer strip due to a rainfall event. By segregating the timeframes where a rainfall event occurred, this same period was used to examine responses of surface runoff, soil moisture, water table height and stream water level at the experiment site. Initial time series analysis included a time period before and after the rainfall event (four hours before and four hours after) to account for any likelihood where the event occurred earlier or later at the experiment site due to the distribution of precipitation over the catchment.

Catchment precipitation (calculated using the above method) was disaggregated using a 6-hour minimum inter-event time (MIT). Determining MIT is subjective with no definitive rule on how rainfall events should be partitioned, however studies by Dunkerley (2008) and Link et al. (2004) highlighted 6 hours as the most common MIT. According to Joo *et al.* (2014) there are three methods that are used to disaggregate rainfall (i) autocorrelation (ii) coefficient of variation ($C_v$) and (iii) mean event count per MIT. The $C_v$ method was disregarded as it would require large MIT to provide an adequate $C_v$ value of close to 1 and Joo *et al.* (2014) highlights that MIT should be kept low for smaller catchments. Autocorrelation is essentially the lag between rainfall peaks and the MIT where the coefficient ($R^2$) gets closer to zero and does not change. This is illustrated in Figure 3.9, which identifies the 8-hour time MIT where $R^2$ does not change and is close to zero. However, the mean event count per MIT method establishes the MIT when the mean number of events does not change between MITs. A 6-hour MIT is identified using this method and is illustrated in Figure 3.10.

Despite two different outcomes from the MIT disaggregation, a comparison of prolonged rainfall events (e.g. of 24-hours or more) between 8 and 6-hour MIT demonstrated smaller events (e.g. less than 12-hours) were being captured within longer rainfall events; which should be considered separate. Thus 6-hour MIT would alleviate this issue. However, it is important to recognise the caveat that any MIT could result in some events being either wrongly split or included together.

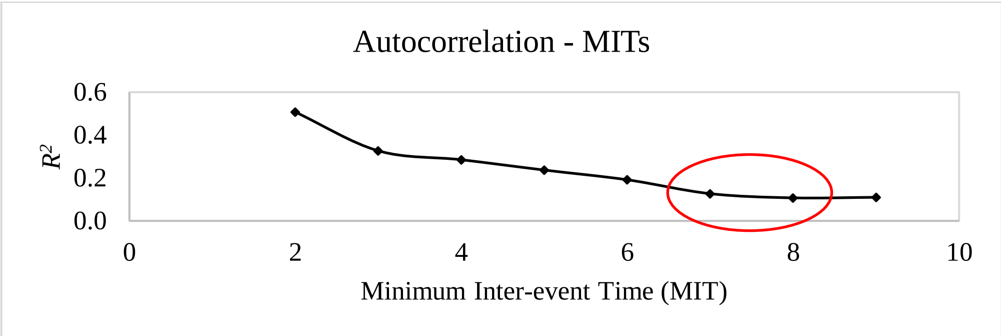



Figure 3.9 Autocorrelation for determining minimum inter-event time (MIT) where the coefficient ($R^2$) nears zero and change in coefficient does not change: 8-hour MIT is the outcome.

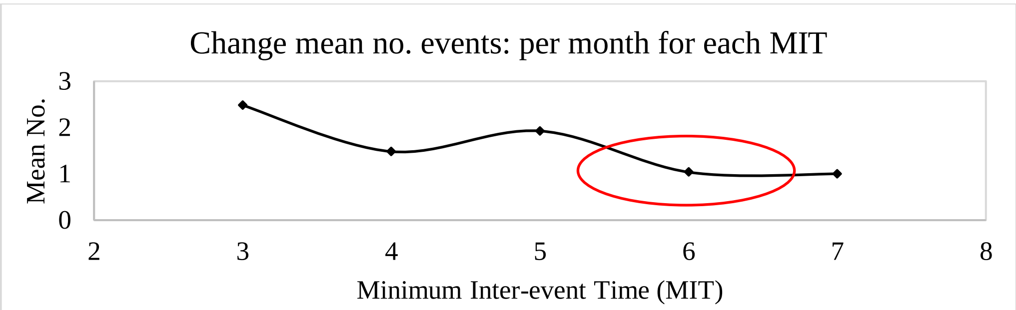



Figure 3.10 Average number of events per month (27 months for experiment period) to determine minimum inter-event time (MIT) where the average number does not change: 6-hour MIT is the outcome.

The 6-hour MIT was defined as beginning when precipitation was >0 and ending when no precipitation had occurred for 6 hours. Each rainfall event was numbered in sequential order from the start of the experiment period (19th December 2013) providing 447 events (up to 14th December 2015). The events could then be analysed in two ways: event conditions and as a time series. It is important to highlight that these 447 events reflect the 447 times there was any precipitation (e.g. some events may only consist of 0.2 mm precipitation).

For each of the 447 events, the following characteristics (i.e. event conditions) of the rainfall event and surface runoff volumes were calculated:

- total event depth (mm);
- event duration (hours);
- mean intensity (mm/hr) which is equal to the depth divided by the duration, and maximum hourly intensity (mm/hr);
- surface runoff flow (Q) (ml/s) Ttp specifies the length of time (hr) from the event start to the highest Q recorded during the event;
- Peak flow (Qpk) identifies the highest recorded surface runoff flow within a defined event; and
- both INRIP and OUTRIP Q were converted to volume per drainage area (mm/m$^2$) with the drainage areas for the INRIP and OUTRIP flumes defined using the 1 m DTM and sound visual judgement of boundaries using contours in ArcGIS.

### *3.3.6 Analysis of land management categories*

The categories of land management derived from the field observations outlined in Section 3.3.2, are defined by the generic conditions of the upslope fields and the adjacent field. The number of fields upslope are categorised into short crop, bare soil or tall crop and the number of fields in which each condition occurs. The adjacent field was categorised based on the field perimeter (which mostly had a different crop to the field centre), the centre of the field, and when there was no perimeter, the whole field. Like the upslope categories, the adjacent field would be categorised as having short crop, bare soil, or tall crop (barley or swede).

A timeline of the land management categories is used to determine the number of events that occurred during each category as well as identify land categories where runoff or only infiltration occurred during rainfall events. The land categories where either an infiltration event or runoff event occurs are then selected for further analysis to ascertain any trends in the conditions of the events that may indicate or distinguish why a runoff enters the buffer strip.

The soil infiltration test results for the unmanaged riparian buffer strip and its adjacent managed arable field are compared to the maximum hourly precipitation depth. This indicated the type of overland flow being generated for runoff events recorded in the riparian buffer strip.

### 3.3.7 Event classification for analysis

To reduce ambiguity of whether V-flume flows were occurring (therefore capturing surface runoff) all (447) rainfall events underwent a filtering process. This also filtered out events with small amounts of precipitation (e.g. 0.2 mm) as the event identification process (Section 3.3.5) delineated all precipitation regardless of depth or duration. Percentiles were used to indicate events with the highest precipitation totals to increase confidence in the V-flume flows recorded being a response to the event.

Percentile values are based on a scale of 100 and each percentile value specifies the percentage of values that are lower than or equal to it (USGS, 2011). For example, if the 95$^{th}$ percentile of river discharge is 2.1 m$^3$/s, the 95$^{th}$ percentile indicates 95% of river discharge values are ≤2.1 m$^3$/s and 5% of river discharge values are >2.1 m$^3$/s. The 95$^{th}$ percentile is referred to a Q5 and the 90$^{th}$ percentile is referred to as Q10 herein.

The rainfall events were filtered by Q5 of precipitation depth (>16.1 mm) and provided 23 events (between 20 December 2013 to 4 December 2015) for further analysis. An attempt to obtain more rainfall events with a runoff response was explored using the Q10 threshold (>10.7 mm) but these additional events were later rejected (see Section 3.3.8).

### 3.3.8 Defining runoff and infiltration events for further analysis

Q5 events were subsequently delineated into infiltration, runoff and rejected events based on the behavioural response of the experiment variables. This would enable an understanding of why some events resulted in surface runoff entering the buffer strip, while others presumably resulted in infiltration. By classifying these events, other factors including: land management, season, antecedent conditions or contributing drainage area, could be examined to ascertain any trends in the event conditions which would result in surface runoff occurring or not occurring.

However, prior to the delineation of event types, the contributing area of surface runoff from the adjacent field was calculated. This determined if the V-flumes were acting as large rain gauges or were connected to the surface runoff from the adjacent field. The calculation applied was a reverse of the Modified Rational Method (Institute of Hydrology, 1999) where Equation 3.1 becomes:

$$A = \frac{Qp}{2.78(C_v \, C_i \, I)}$$

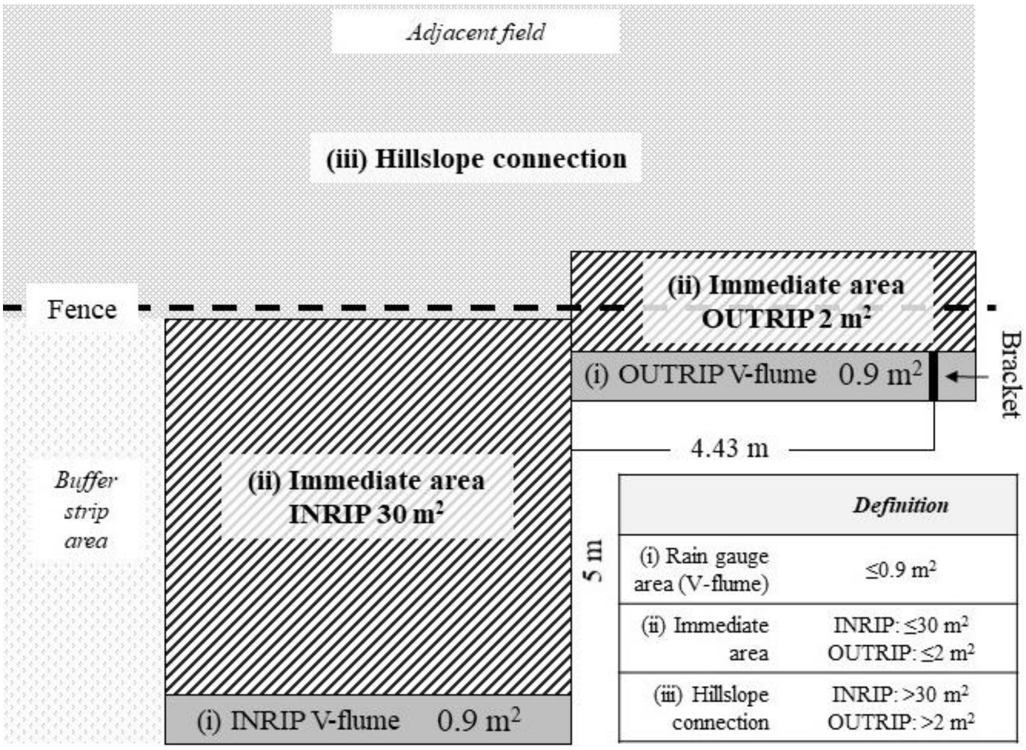
Equation 3.12

Where: $Q_p$ is the peak runoff rate (ml/s); $C_v$ is the volumetric runoff coefficient; $C_i$ is the routing coefficient; *i* is the average rainfall intensity for a duration equal to the time of concentration (mm/hr); and *A* is the catchment area (ha).

Cumulative depths (mm) of both rainfall and V-flume surface runoff were calculated and compared for each event using graphical analysis. This would determine if the calculated runoff drainage area was larger than the V-flume area or immediate area around the V-flumes, thereby indicating a connection to a larger drainage area of the hillslope. It was necessary to establish this method due to later evidence that the buffer was being disconnected from the riparian buffer strip by plough furrows or tramlines (tracks left by agricultural machinery in fields) (evidence shown in Chapter 5 and discussed in Chapter 7).

The adjacent field soil type was classified as HOST 17 with a standard percentage runoff (SPR) of 29% (Boorman et al., 1995) therefore, it was assumed 29% of precipitation would result in runoff. Three types of surface runoff responses were taken into consideration in conjunction with the decision framework in Figure 3.12: (i) whether the V-flumes were acting as a rain gauge, (ii) collecting surface runoff from the immediate area of the buffer strip, or (iii) connected to the hillslope (Figure 3.11):

i. The 'rain gauge area' was considered as the area of the concrete V-flumes (refer to Figure 3.4): 4.43m long (from bracket) and 0.2m wide = 0.9m$^2$. If the back calculated drainage area (Equation 3.12) is ≤0.9m$^2$, the event would be considered a "rain gauge" event and rejected for further analysis.
ii. The 'immediate area' was defined as the remaining area of riparian buffer strip between the field and the V-flume and determined using spatial analysis in ArcGIS: INRIP = up to 30 m$^2$ and OUTRIP = up to 2 m$^2$.
iii. A 'hillslope connection' (and thereby a runoff event) was defined where the contributing drainage area for the flow recorded in the V-flumes was: INRIP = >30 m$^2$ and OUTRIP = >2 m$^2$.




| | Definition |
|---|---|
| (i) Rain gauge area (V-flume) | $\leq 0.9$ m² |
| (ii) Immediate area | INRIP: $\leq 30$ m² OUTRIP: $\leq 2$ m² |
| (iii) Hillslope connection | INRIP: $>30$ m² OUTRIP: $>2$ m² |

Figure 3.11. Three types of runoff source area (i) rain gauge area (V-flume) (ii) immediate area and (iii) hillslope connection. Each runoff source area was determined to classify whether runoff recorded during a rainfall event was connected to the hillslope or the V-flumes were acting as a large rain gauge.

The calculated contributing runoff areas supported the ability to classify the *type* of event which occurred at the experiment site. By monitoring surface runoff, stream level, water table height and soil moisture, events could be segregated into the following types of events (shown in Figure 3.12):

i. Rejected event:
   a) Where there was no response from any of the variables, likely due to localised rainfall distribution *or*;
   b) Where data is missing due to equipment failure *or*;
   c) Where there is measurement error from diurnal influence (outlined in Section 3.3.11).

ii. Infiltration only:
   a) A response from soil moisture but no response from the surface runoff *or*;
   b) A response from soil moisture and the response from INRIP and OUTRIP runoff is determined to be from the 'immediate area' or equivalent to acting as a rain gauge (as defined above).
   c) A response from water table height and/or the stream stage would further clarify this type of event but is not a deciding factor.

iii. Runoff event:
   a) Signified by a response from soil moisture *and*;

b) A response from OUTRIP surface runoff *or* INRIP surface runoff for which the contributing drainage area is determined to be connected to the hillslope.

c) A response from the water table height and/or stream level further vindicated this type of event but is not a deciding factor

Figure 3.12 outlines the decision-making framework for classifying the events into 'runoff', 'infiltration' or 'rejected'. The response from the OUTRIP surface runoff was the initial deciding factor as this would demonstrate whether surface runoff had entered the buffer from the adjacent field. Where an event has a response in the V-flumes it would indicate it was connected to the hillslope. If there was diurnal uncertainty, events would be rejected due to the uncertainty as to whether runoff or infiltration occurred. In addition, the discharge data for Coull and Aboyne was also compared for each event to determine whether the catchment responded to a precipitation event, which would account for a larger scale response.

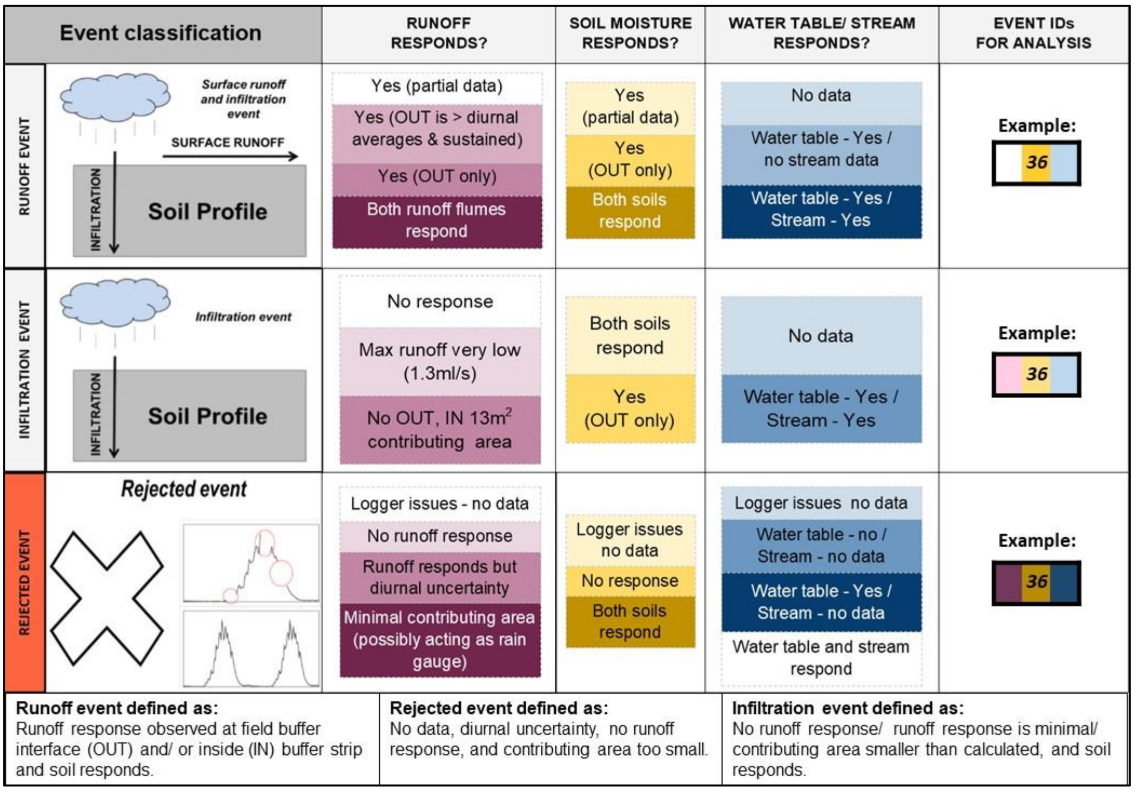



Figure 3.12. Event classification decision framework. Left to right, the decision framework defines the classification of event and subsequent columns determine how that decision is made with the most important deciding factor being (i) runoff response (ii) soil moisture response and (iii) water table/stream response, respectively.

### *3.3.9 Analysis of event conditions*

For each infiltration, runoff and rejected event, summary statistics of the event conditions outlined in Section 3.3.5 were calculated. Event conditions that were considered are: precipitation (pcp) depth (total amount of catchment precipitation for the event), event duration (using 6-hour MIT rule, number of hours precipitation occurred), precipitation intensity (where total catchment precipitation depth is divided by duration), maximum intensity (the highest hourly catchment precipitation), and API30. Minimum and maximum temperature of the event were also considered.

In order to address RQ1 and determine the conditions by which overland flow entered the riparian buffer strip, the following analyses on the event conditions (e.g. precipitation depth and duration) were conducted:

- Summary statistics (median, minimum and maximum) and boxplots to assess the distribution of event condition variables between infiltration events and runoff events. This intended to establish whether distributions of each event condition differ for infiltration or runoff events.
- Mann-Whitney test to compare the difference between the median values of each event condition for infiltration and runoff events. This determined if there is a statistical difference between each event condition of the infiltration events and runoff events; and identified whether the difference is significant (where *P*-value is $<0.05$). If a significant statistical difference is determined for any of the event conditions, this would indicate the condition(s) (e.g. precipitation depth) values could potentially determine whether an infiltration or runoff event occurs. However, this would require further analysis.
- Each event condition was ranked from highest to lowest to establish any trends in the event conditions when a runoff event (or infiltration event) occurred. Analysis of ranked event condition values would highlight possible thresholds which may determine if an event results in infiltration or runoff.

The ranking of each event condition, independently, also included land management categories and season to assist in explaining trends and initially exploring these other influencing factors.

### *3.3.10 Analysis of the influence of land management and seasonal event conditions on runoff events*

The purpose of this analysis was to establish whether land management of the adjacent field or the seasonality of the event conditions (or both) was influencing runoff events. The influence explored was whether these factors increased the magnitude of runoff peak, runoff volume, or the contributing area of runoff. Due to the limited size of dataset, solely assessing season was not feasible, but assessment of event conditions and their seasonal differences would enable an understanding of the three influencing factors (event conditions, season, and land management).

Seasons were defined using the Met Office (2017b) definition whereby: December to February is winter, March to May is spring, June to August is summer, and September to November is autumn. As outlined in Section 3.3.2, land management changes were recorded using monthly photographs. Common land uses in the catchment are arable (e.g. barley and hay), and pasture (sheep and cattle grazing).

Graphical analysis of OUTRIP Qpk, OUTRIP volume of runoff, OUTRIP runoff time to peak (Ttp), and OUTRIP contributing runoff area for each runoff event were contrasted with event conditions, seasons of occurrence, and land management practices to provide an overview of trends. Where these trends required further explanation, photographic evidence of land categories were compared.

#### *3.3.11 Measurement errors*

This study involved the collection of multiple types of field data using a variety of instruments, as well as using data from partner institutes and third-party data providers. This was then processed and analysed. Each step in this process introduces the likelihood of errors which will be outlined in turn:

- Field equipment have their independent accuracies depending on the provider and spec of equipment. Maintenance and calibration were essential to ensure sensors remained functional within their accuracy thresholds.
- Despite following British standard protocol, the soil infiltration test could also have an element of error depending on whether the single ring infiltrometer was deployed to the correct depth and at an appropriate angle. This test was conducted in one area of the buffer strip and adjacent field and may coincidently have been conducted in an area inconsistent with the whole field or buffer strip.
- User error can also be introduced whereby use of software, equipment or statistical analysis is either not conducted appropriately or the user is unaware of other errors; for example, in the datasets or calculations.
- Equations which used coefficients or estimations (for example, of evaporation rates) are simply estimations. These may not be entirely accurate.
- Discharge data relies on rating curves for more accurate representation of flows, which in themselves have inaccuracies and uncertainty
- The DTM used has a 1 m resolution, which may also have inaccuracies within the data from when it was obtained using airborne LiDAR flights or how it was post-processed.

### 3.4 Research question 2 – supporting ecosystem services

*RQ2: What is the impact of riparian buffer strips on algae biomass in streams as an indicator of nutrient cycling and primary production?*

The second aspect of the empirical field study was conducted to establish the impact of riparian buffer strips on supporting ES (nutrient cycling and primary production) by comparing algae concentrations at sites with and without a riparian buffer strip. Algae are indicators of the ecological response to nutrient loads (nutrient cycling), as well as other influences (e.g. temperature and hydrology), and the subsequent primary production (illustrated in Figure 2.6, page 33). Higher concentrations of algae biomass can indicate greater nutrient loads (depending on other influences) and thereby enhanced cycling of these nutrients (Figure 2.6) by the algae (although high levels of nutrients can become limiting). With greater algae biomass, primary production is also increased.

This study compared algae (phytoplankton) biomass by measuring Chl-a concentration within each stream using an algae torch. Using European Water Framework Directive (WFD) standards, the Ecological Quality Ratio (EQR) was calculated and formed the basis of determining the cascading response of algae biomass to nutrients, which increases primary production and can impact on multiple ES (e.g. fish production, water quality regulation and recreation). These impacts were captured in a framework which used literature to indicate the potential impacts on wider ES (Section 3.4.2).

A subsidiary intention with this aspect of the study is not only to provide a simultaneous assessment of impacts that riparian buffer strips have on flood risk and ES, but to explore the use of simplistic equipment (algae torch) to achieve interdisciplinary research. Catchment science and FRM fields are progressively being required to further understand other disciplines, especially when implementing NFM and determining the multiple benefits of measures. Understanding the impact riparian buffer strips have on algae concentrations and in turn ES, can contribute towards quantifying the multiple benefits as an NFM measure.

### *3.4.1 Experiment locations*

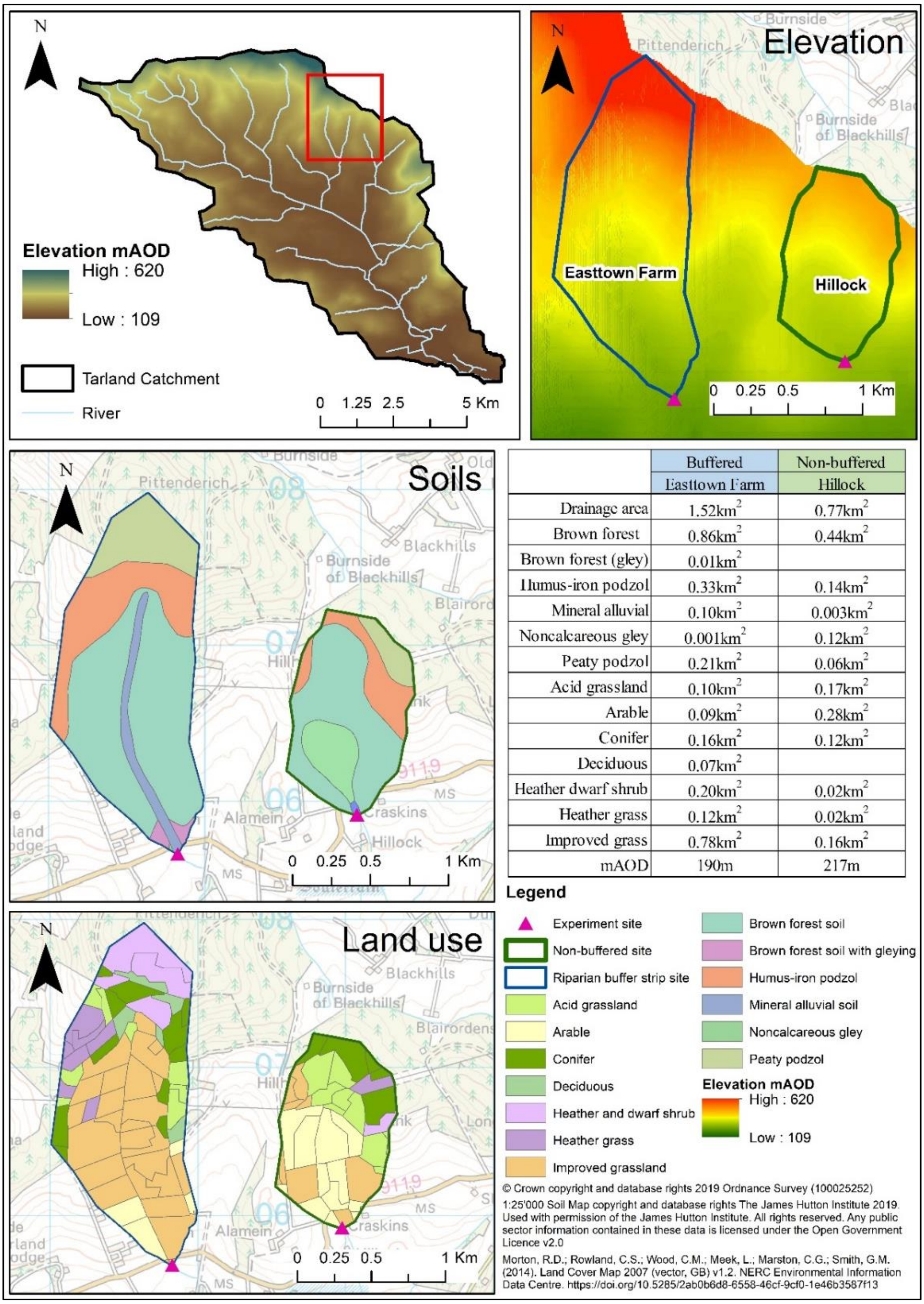
Two sites were used for the ES element of the study: the runoff experiment site at Easttown Farm (outlined in Section 3.2.2) which has a riparian buffer strip (buffered site), and another paired catchment site at Hillock (Figure 3.2 and Figure 3.13) without a riparian buffer strip (non-buffered site). The non-buffered experiment site was selected based on the similarities to the buffered site (outlined in Section 3.2.2).

### *3.4.2 Framework of ecosystem services provided by algae*

The framework for ES was developed to enable an understanding of how algae concentrations can affect ES and have a knock-on effect on other ES. The intention of this framework is to provide a reference to support understanding of the wider impact of the study sites' ecological status on ES (see Section 3.4.5 for details). A pictographic framework was developed (presented in Section 5.3.2 of Chapter 5 Experimental results) using literature to generalise the relationships and influences that Chl-a (algae concentration) functions have on wider ES and how the supporting ES of Chl-a functions can have a cascading impact on other ES, which are mostly at larger spatial scale. The framework identifies what can influence Chl-a concentration, what Chl-a require for algae to survive and exist; and the functions that algae perform in their environment. The ES provided by algae are summarised by type of service: supporting, regulating, provisioning and cultural, using the MEA classification (Millennium Ecosystem Assessment, 2005). The functions performed by algae are then linked to the type of ES which they influence. This framework is also used to understand feedback mechanisms where influences on algae biomass are also affected by the ES they provide.

### *3.4.3 Existing data*

Only the buffered site has pre-existing (water quality, rainfall and temperature) data. A full outline of monitoring and missing data periods for each variable (pre-existing and monitored during this study) are outlined in Table 3.1 (page 42). This existing data enabled further assessment to explain algae concentration trends at each site or where differences between the sites were evident. Albeit, this data enabled further explanation of trends at the buffered site only. The data used to supplement the explanation of algae concentration trends included: monthly land management conditions, meteorological conditions and monthly water quality conditions.




| | Buffered | Non-buffered |
|---|---|---|
| | Easttown Farm | Hillock |
| Drainage area | 1.52km$^2$ | 0.77km$^2$ |
| Brown forest | 0.86km$^2$ | 0.44km$^2$ |
| Brown forest (gley) | 0.01km$^2$ | |
| Humus-iron podzol | 0.33km$^2$ | 0.14km$^2$ |
| Mineral alluvial | 0.10km$^2$ | 0.003km$^2$ |
| Noncalcareous gley | 0.001km$^2$ | 0.12km$^2$ |
| Peaty podzol | 0.21km$^2$ | 0.06km$^2$ |
| Acid grassland | 0.10km$^2$ | 0.17km$^2$ |
| Arable | 0.09km$^2$ | 0.28km$^2$ |
| Conifer | 0.16km$^2$ | 0.12km$^2$ |
| Deciduous | 0.07km$^2$ | |
| Heather dwarf shrub | 0.20km$^2$ | 0.02km$^2$ |
| Heather grass | 0.12km$^2$ | 0.02km$^2$ |
| Improved grass | 0.78km$^2$ | 0.16km$^2$ |
| mAOD | 190m | 217m |

Figure 3.13. Paired catchment experiment site locations and characteristics including elevation, soils and land use. A comparison and breakdown of the coverage of soil and land use type per site is shown in the integrated table.

The land management data is provided by monthly photographs of the buffered site, which are outlined in Section 3.3.6. In addition to the method outlined in Section 3.3.6, the land conditions were transcribed into a schematic which identified the land management conditions for both sides of the stream (illustrated in the *land use* box as orange and yellow land parcels Figure 3.13), rather than only the left bank fields that were assessed as part of RQ1. The land management is not assessed as categories as they were in Section 3.3.6, only as representative bird's-eye-view illustrations. It would add an additional layer of complication to include another land category type to enable consideration of the right bank fields and hence, a schematic was used.

As meteorological data was collated and processed for RQ1 and RQ3, it was also utilised to understand trends in algae concentrations of the buffered and non-buffered site. Algae is affected by precipitation as it alters streamflow conditions as well as influences the degree of overland flow, which can transport nutrients and impact algae concentrations. Algae growth is also fuelled by higher temperatures. Precipitation, temperature and antecedent conditions (API30) were compared to algae concentrations to ascertain any coincidental trends and explore reasons why some concentrations were higher or lower than expected. Catchment precipitation depth, as outlined in Section 3.3.3, was totalled for the 30 days prior to sampling to provide a standardised approach to assessing each sample month. Due to there being variability in the number of days between each sample month, accounting for the last 30 days would be consistent across each monthly comparison between the buffered and non-buffered site. Additionally, the API30 was used and methodology for calculation is outlined in Section 3.3.4. This was used in parallel to the 30-day catchment precipitation total as it accounted for evaporation and subsurface losses (using a decay factor). The maximum, minimum and average temperature on the day of sampling was utilised to understand whether daily temperature trends coincided with algae concentration trends. The average monthly temperature, however, was used to assess any seasonal temperature influence. Meteorological data is present graphically.

Monthly water quality data obtained by JHI at the experiment site (separate to this research project; Figure 3.2) was graphed and compared to the algae concentrations of the buffered and non-buffered site. Algae is mostly reliant on phosphorus as a nutrient for growth, but also influenced by nitrogen. Therefore, the following JHI water quality data was also compared graphically to algae concentrations:

- Nitrate ($NO_3$-N)
- Total nitrogen (Total-N)
- Ammonium ($NH_4$-N)
- Total phosphorus (Total-P)
- Phosphate ($PO_4$-P)

All existing data supplemented the results of the algae experiment at the buffered and non-buffered site. Following the comparison between both sites, this data was compared to the algae concentrations at the buffered site to assess any trends and indicate why they may be different, or similar, to the non-buffered site.

### *3.4.4 Experimental setup: algae concentrations*

As part of this study, concentrations (mg/l) total Chl-a (algae concentration) were monitored in the buffered and non-buffered stream. An algae torch (bbe moldaenke © manufacturer) recorded measurements each month from April 2014 to June 2015. At both the buffered (Easttown Farm) and non-buffered (Hillock) sites, a 50 m transect of the stream was measured and flags identified each cross-section of the stream transect where the algae torch measurements were to be taken. Figure 3.14 demonstrates this setup, highlighting the cross-sections being 5 m apart over the 50 m transect. There are 11 cross-sections in total per transect and at each one, a measurement is taken from the left bank, right bank, and stream centre. Measuring the Chl-a concentrations at 33 points along the 50 m transect allowed statistical analysis to be conducted as there would be more than 20 data points. Monitoring the Chl-a concentrations would indicate the abundance of algae within the 50 m transect at each site. In turn, using the framework in Section 3.4.2, these concentrations would indicate their linkages to in-stream ES and highlight whether the buffered or non-buffered site provided multiple benefits by regulating algae concentrations.

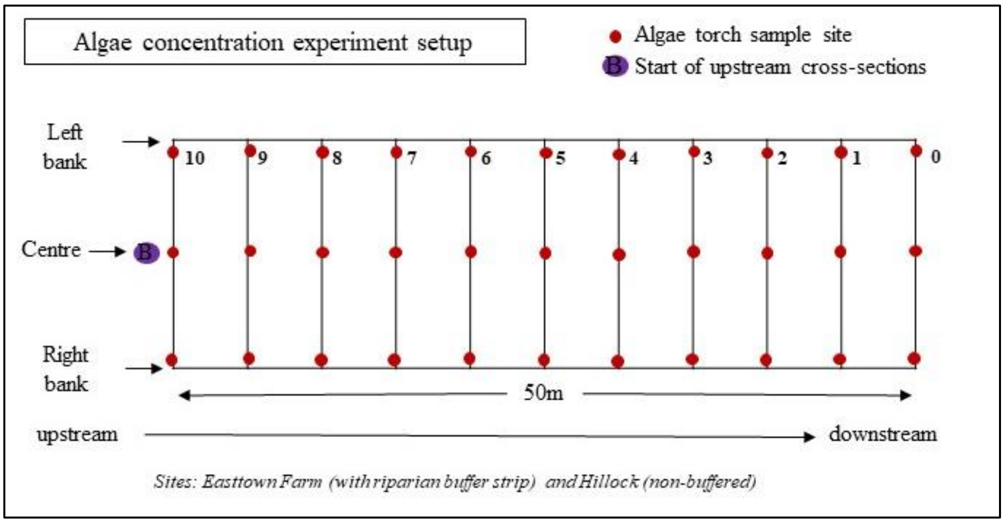



Figure 3.14. Algae torch experimental setup schematic. Transects every 5 m along a 50 m stretch of stream and a measurement taken at the right bank, centre and left bank at each transect.

Due to mechanical issues with the algae torch (especially in colder months) and difficulty accessing the stream in summer (because of vegetation growth at the buffered site), data was not collected for specific months, which are identified in Table 3.5. Therefore, direct comparisons between the buffered and non-buffered site could only be achieved for months where data was obtained from both sites (Table 3.5). These months are:

- April to May 2014
- August to November 2014
- February to March 2015
- May 2015

Table 3.5. Months of algae torch data (X) collected during 2014 and 2015. Missing data (O) is either due to battery failure, vegetation being too dense to access the stream, or the instrument was being serviced by the manufacturer.

| | ***2014*** | | ***2015*** | |
|---|---|---|---|---|
| | ***Buffer Strip*** | ***No Buffer*** | ***Buffer strip*** | ***No buffer*** |
| Jan | | | O | X |
| Feb | | | X | X |
| Mar | | | X | X |
| Apr | X | X | O | O |
| May | X | X | X | X |
| Jun | X | O | O | X |
| Jul | O | X | | |
| Aug | X | X | | |
| Sep | X | X | | |
| Oct | X | X | | |
| Nov | X | X | | |
| Dec | O | O | | |

### *3.4.5 Data analysis: Ecological Quality Ratio*

The UK Technical Advisory Group (UKTAG) on WFD set specified standards by which water quality is measured (WFD-UKTAG, 2014). One element of these standards is the EQR which determines the status of water bodies as being: high, good, moderate or poor. The EQR is determined for multiple biological and environmental standards (e.g. macroinvertebrates, macrophytes, invasive species, and geomorphology). Specific to this study, the UKTAG EQR method for assessing phytoplankton biomass using Chl-a were applied. The purpose of using this method is to establish whether the buffered site and non-buffered site have similar or different EQR scores and determine their status. According to SEPA (SEPA, 2017) the Tarland Burn is currently *less than good* status overall but considered *good* for phytobenthos (which would include sestonic algae); and *moderate* for fish ecology .

In Scotland, there are no set limits for Chl-a concentrations in rivers; only in lakes. Chl-a is used by UKTAG as a proxy to measure phytoplankton (algae) biomass, which indicates the degree of primary production. Thus, understanding the food available to higher trophic levels in the food web as well as any risk of eutrophication. The role of Chl-a in nutrient cycling and other ES are outlined in Chapter 2 and Chapter 5.

The UKTAG methodology for determining the concentration of Chl-a to establish the EQR and subsequent water body status is outlined below. It should be noted that the approach used by UKTAG for Chl-a in lakes is adopted in the absence of alternative methods for riverine ecosystems. Consequently, there is uncertainty with the determination of EQR and status for Chl-a. However, conditions required for calculations have been adopted in a manner that best represents a small stream.

UKTAG methodology first requires definition of the type of 'lake' and due to the buffered and non-buffered sites having small streams, the *low alkalinity, very shallow* (≤1 m) lake type was selected. This provided a range in which the geometric mean of $LOG_{10}$ Chl-a should fall between when calculated from observations: 0.3 µg/L – 6.0 µg/L (note that level of alkalinity was the same for moderate alkalinity and the high alkalinity (values were between 5.0 µg/L – 5.9 µg/L) therefore it was assumed alkalinity would be low or moderate based on JHI monthly water quality data showing pH to be sustained between 6.9 and 7.6).

UKTAG methodology advises obtaining three years of monthly Chl-a observations to allow an annual geometric mean to be calculated that will account for seasonal differences. As this study obtained observations from April 2014 to May 2015, the annual geometric mean was calculated from average monthly $LOG_{10}$ Chl-a from April 2014 to March 2015, covering one year and all seasons. The *expected* Chl-a concentration is then calculated by:

$$Chl_{Ref} = 10\ (0.223 + 0.166 *\ \log 10\, Alk) + 0.684\ \left(\sqrt{1/_{depth}}\right)$$

Equation 3.13

Where: $Chl_{Ref}$ is the geometric annual mean chlorophyll a concentration (µg/L); $Alk$ is alkalinity (mEq/l) (minimum value of 0.005 was used); and *depth* is mean depth (m) (minimum value of 1.0 was used). The $Chl_{Ref}$ should be between range of 0.3 µg/L – 6.0 µg/L estimated by the lake type (low alkalinity and very shallow). To then calculate the Chl-a EQR ($EQR_{Chl}$) the following calculation was used:

$$EQR_{Chl} = \frac{Chl_{Ref}}{Chl}$$

Equation 3.14

Where: *Chl* is the observed Chl-a concentration (µg/L). The $EQR_{Chl}$ boundary values used to determine the Chl-a WFD status are outlined in Table 3.6 (WFD-UKTAG, 2014).

Table 3.6. UKTAG Chlorophyll-a EQR score boundaries for each status classification (WFD-UKTAG, 2014).

| *High/Good* | *Good/Moderate* | *Moderate/Poor* | *Poor/Bad* |
|---|---|---|---|
| 0.63 | 0.3 | 0.15 | 0.05 |

The Chl-a EQR scores were then compared between the buffered and non-buffered sites. This comparison would identify whether the buffered site had a healthier EQR score and whether the sites had different status classifications. The purpose of this is to determine whether riparian buffer strips have an impact on algae concentrations, thereby addressing RQ2.

### *3.4.6 Data analysis: graphical analysis of algae concentrations*

Graphical analysis consists of a series of line or bar graphs which are visually assessed. A graphical analysis comparing the median algae concentrations at the buffered and non-buffered site was used to establish any trends at each site and understand if these trends were reflected at both sites. This would identify months where further data analysis was required to assess other factors that may be influencing trends. These factors are outlined below and include weather, nutrients, and land management. Graphical analysis was used to identify any seasonal trends.

### *3.4.7 Data analysis: Mann-Whitney statistical test*

The buffered and non-buffered sites were statistically assessed to establish if they are different from one another and whether that difference is statistically significant. If the sites were to be determined statistically different this would indicate the algae concentrations differ from a buffered and a non-buffered site. To address RQ2, a Mann-Whitney statistical test was used as the data were not normally distributed and would establish whether the median value of all 33 data points at each site were significantly different. Median is used in Mann-Whitney statistical tests to mitigate the influence of outliers which are prevalent in data that are not normally distributed. This test was conducted in Minitab statistical software, which employs the following method:

- For each month where data existed for the buffer and non-buffered site, each site's individual data points were ranked from lowest to highest.
- The middle value, the median, for each site was then compared to establish any difference.
- Using a 95% confidence level, the *P*-value established whether any differences were significant if it was <0.05.

A graphical analysis of median Chl-a concentrations was used to assess and compare trends at each sample site. The results of the graphical analysis were explored further by assessing weather, land management and nutrient data to ascertain other possibilities as to why trends occurred.

### *3.4.8 Data analysis: comparing weather, land management and nutrient concentrations to algae trends*

To explore other factors (other than the riparian buffer strip) that may influence Chl-a concentrations, weather data was compared to the monthly median Chl-a concentration at each site using graphical analysis and tabular data. The weather elements used to assess this included:

- 30-day total of catchment precipitation (described in Section 3.3.3);
- API30 (defined in Section 3.3.4)
- Mean, minimum and maximum daily temperature (on the day of algae torch measurement);
- The number of Q5 events (determined in Section 3.3.7);
- Water temperature at the buffered and non-buffered site.

Despite there being less than 20 samples to enable adequate statistical analysis, scatter plots for each weather variable and the Chl-a concentrations at each site to indicate trends. This would provide some indication of relationships between Chl-a and weather variables.

There was more data available on land management at the buffered site from the monthly photographs taken to categorise the land management for the runoff experiment (Section 3.3.6). These photographs existed for the fields upstream and downstream of the runoff site and were transcribed into a schematic outlining the land management in the fields upstream of the algae torch sampling sites on the right and left bank. The description was simplified as: bare soil, short crop, tall crop and pasture. Included in this were the land descriptions for the adjacent field to the runoff experiment (short crop perimeter and either swede centre or bare soil centre). The schematic displayed the land management in each field the respective months where algae concentrations were recorded at the buffered site.

At the non-buffered site, some photographs were taken during field visits of any site conditions that may affect the Chl-a concentrations. Although not as thorough as the land management photographs obtained at the buffered site, these provide valuable evidence that was used to explain median Chl-a trends. The photographs were presented and described in relation to the trends observed from graphical analysis of median Chl-a concentrations.

Nutrient data for the buffered site existed as JHI sample the same site on a monthly basis and provided the data to include in the analysis. The nutrient data consists of $NH_4$-N, $NO_3$-N, Total-N, $PO_4$-P, Total-P, and DOC. As relationships between these nutrients and Chl-a are well established, the Chl-a trends could be analysed further at the buffered site to explain why some trends differed from the non-buffered site. Unfortunately, the land management and nutrient data did not exist for the non-buffered site. The nutrient data was analysed using graphical analysis and testing regression relationships through fitted line plots. As stated previously, the sample size was insufficient to produce robust and certain statistical analysis, but the relationships could be examined but with caution.

## 3.5 Chapter summary

This chapter has outlined the methodology utilised to address RQ1 and RQ2. The following sections summarise the methods employed to address each RQ.

### *3.5.1 Summary of analysis for research question 1*

The analysis methods utilised to address RQ1 involved multiple elements to understand the influences on runoff entering the riparian buffer strip. The following analyses were used:

- A timeline of land management practices in the adjacent and upslope fields from the experiment site derived from monthly photographs. These timeframes were compared graphically and in tabular form to ascertain any trends that would indicate land management influences on runoff entering the buffer strip.
- Analysis of infiltration rates and precipitation intensities to ascertain the likely overland flow type(s) that occur at the experiment site.
- Analysis of precipitation events and selected Q5 events to assess the response at the riparian buffer strip. Q5 events were one of several solutions to mitigate uncertainty from diurnal fluctuations in the runoff observations.
  - Definition of infiltration and runoff responses to events to mitigate uncertainty in runoff measurements. These events were then compared against land management practices at the time of event, and calculated event conditions (e.g. precipitation depth and antecedent conditions). This would identify trends and whether these elements appeared to be a factor in runoff entering the riparian buffer strip.
- Calculation of the drainage area contributing runoff to the riparian buffer strips and the average ‘depths’ recorded by the runoff measuring equipment on days with no rainfall. This enabled the assessment of runoff events that were uncertain and were rejected based on likely diurnal fluctuations or defined as infiltration events based on drainage area.
- The conditions by which runoff entered the riparian buffer strip were also assessed by using summary statistics of the runoff volume, soil moisture and event conditions. Mann-Whitney statistical tests were conducted to determine differences between median event condition values for infiltration and runoff events. Finally, ranking of event conditions enabled assessment of event trends during runoff and infiltration events.

### *3.5.2 Summary of analysis for research question 2*

The analysis methods utilised to address RQ2 involved a comparison of Chl-a concentrations at the buffered and non-buffered site as well as an examination of possible influences on monthly Chl-a trends including weather, land management and nutrients. The following analyses were used:

- The WFD-UKTAG EQR was calculated to establish whether the buffered and non-buffered site were similar or different. This would imply whether the riparian buffer strip site improved nutrient cycling and primary production (supporting) ES.

- A framework of the linkages between Chl-a and wider ES was derived from literature and provided a reference for further discussion about the impact of the Chl-a concentrations, EQR and status on ES.
- Graphical analysis enabled trends in median Chl-a concentrations at the buffered and non-buffered site to be compared. This assisted in identifying trends where Chl-a concentrations were high or replicating seasonal differences.
- Mann-Whitney statistical testing was used to establish whether the buffered and non-buffered stream Chl-a concentrations were statistically different on a month to month basis. This test would highlight when there were differences and identify months where further assessment of supplementary data (land management, weather and nutrients) could provide further insight.
- Land management, weather and nutrient data was contrasted to the monthly median Chl-a concentrations to ascertain their influence and provide additional understanding for any unusual trends.

# Chapter 4 Modelling methodology

## 4.1 Introduction

The aim of this thesis is to establish whether riparian buffer strips are effective NFM measures by providing multiple ES, including flood regulation. The flood regulation ES is examined at field scale using an experimental monitoring approach however, at catchment scale a hydrological modelling approach is required to understand the landscape scale impact of riparian buffer strips on flood risk. The methodology set out in Chapter 3 is specific to the *field* scale element of flood regulation, nutrient cycling and primary production ES of this study whereas; this chapter is focused on flood regulation at the catchment scale (Figure 1.1, page 4) and addresses the following RQ:

RQ3: How effective are catchment-wide riparian buffer strips at reducing peak flow and what is the most effective riparian buffer strip width and vegetation type (using SWAT model as a tool)?

a. What width of catchment-wide riparian buffer strip reduces peak flow ($m^3/s$) most effectively at upper, middle and lower catchment scale?
b. Do grass-based or tree-based riparian buffer strips provide a greater reduction in peak flow?

Hydrological models are tools used for understanding and estimating hydrological processes and planning water resource management. These models are utilised for a range of purposes including:

- Predicting processes that are not currently quantified or cannot be measured (due to limitations of hydrological measurement) (Beven, 2012);
- Assessing different scenarios and informing knowledge of hydrological processes; and
- Strategic planning of where to focus efforts in catchment management.

SWAT has been used to assess agricultural land management and climate change (Wagena and Easton, 2018), runoff and sedimentation in watersheds (Qiu et al., 2012) and the impact of land use change on water resources (Baker and Miller, 2013). Hydrological models are an integral tool for decision making on flood management, pollution, land use planning and many other sectors (Beven, 2012). As part of this study, SWAT was utilised to investigate potential outcomes if riparian buffer strips are applied catchment-wide at different widths and with different types of vegetation (grasses and trees). As the experiment for this study is local and field based, hydrological modelling can enable an upscaled portrayal of catchment response to various riparian buffer strip scenarios; provided there is confidence that the processes are well represented in the model.

Later discussion (Chapter 7) will explore the use of SWAT for investigating catchment scale implementation of riparian buffer strips. Evaluating the effectiveness of SWAT for modelling riparian buffer strips will contribute to academic understanding of the appropriateness of the model for such studies and offer insights into how the model may be fine-tuned for improved model processing. Reasons for using SWAT and a comparison between other scoped hydrological models are summarised in Chapter 2. In this chapter, the method used to build SWAT, apply scenarios and analyse simulated results are outlined.

### *4.1.1 Spatial and temporal scales of modelling*

SWAT is intended to be applied at catchment scale (i.e. watershed or river basin scale; Table 2.2) and the purpose of using SWAT in this study was to ascertain the impact of riparian buffer strip scenarios on peak flows at catchment scale. Nevertheless, the simulation results were assessed in the upper (25.3 $km^2$), middle (24.3 $km^2$) and lower catchment (18.2 $km^2$; demonstrated in Figure 4.1) to understand whether the response to the buffer scenarios were uniform, cumulative or distinct across the catchment. A subsidiary spatial scale assessment was undertaken at the corresponding site of the experiment to highlight how SWAT performs at such high spatial (field scale) resolution (0.33 $km^2$) in a model calibrated at catchment scale. However, Baffaut et al. (2015) has indicted that a model calibrated at a larger spatial scale is unlikely to be representative of field-scale conditions due to inherent assumptions required for catchment scale models. The spatial scales analysed using SWAT are from field to upper, middle and lower catchment scale. The stream flows recorded at the experiment site are compared to the simulated flows at the same location in the model setup of the catchment; whereas the upper, middle and lower catchment scale flows are compared against flows recorded on the main river stem by third parties.

Temporally, SWAT requires a daily resolution of simulation prior to hourly resolution being applied. SWAT Calibration Uncertainty and Prediction (SWAT-CUP) software (Abbaspour, 2015) was utilised for daily calibration, and some of these parameters informed the hourly calibration. Tarland catchment required hourly resolution to capture high flow events in responding to rainfall events as response times were less than a daily resolution.

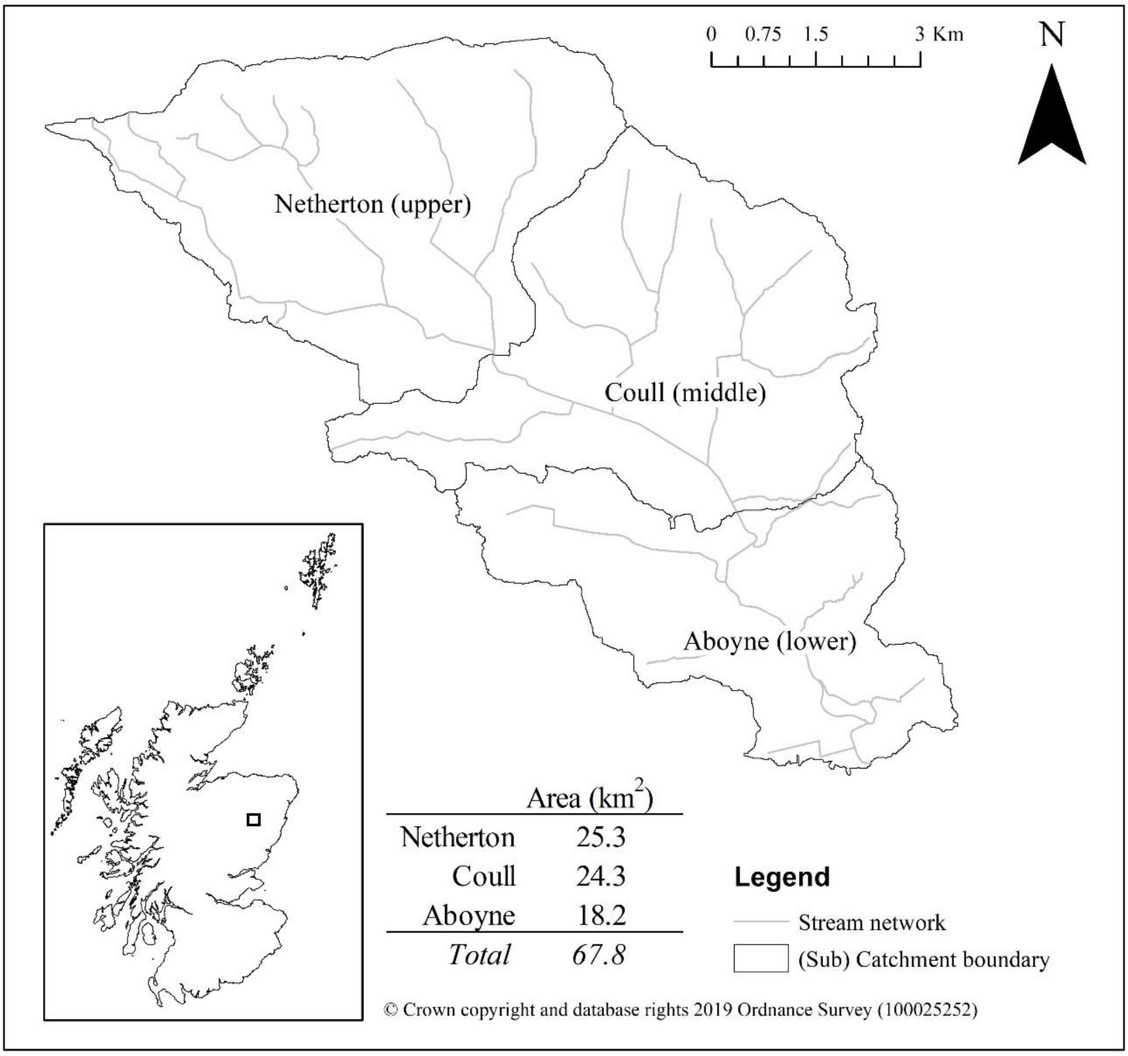



Figure 4.1. Spatial scales of analysis for modelled scenarios. The upper (Netherton), middle (Coull) and lower (Aboyne) sub-catchment areas where observed data exists, and model scenarios were compared.

### 4.2 SWAT model description

SWAT is a process-based semi-distributed hydrological model. It is well established and widely used internationally. The watershed is delineated by dividing the catchment into sub-basins. The addition of required land use, soils and slope data subsequently enables the sub-basins to be further delineated into HRUs based on the various combinations of these three central data inputs. This break down of the catchment into smaller sub-basin and HRU components facilitates the model's ability to simulate the hydrological response to changes in management practices, land use, and climate at the watershed, sub-basin and HRU level (Baker and Miller, 2013; Dechmi et al., 2012). HRUs are a compromise between lumped and fully distributed hydrological models to minimise computational effort but enables the capture of explicit differences in soils, land use and slope.

SWAT can be utilised for annual to hourly temporal resolution of flows. This study utilised an hourly resolution as the Tarland catchment is relatively small (73 km$^2$) and flood or high flow events occur a smaller than a daily resolution. SWAT requires multiple datasets for the different components: topography, land use, weather and soil (Panhalkar, 2014). The most recent version of the model, SWAT2012 (Arnold et al., 1998; Arnold and Fohrer, 2005), was utilised for this study in the form of the ArcSWAT plug-in for ArcGIS mapping software (ArcSWAT 2012.10.21; rev.620 for ArcGIS 10.3.1). A sister software package, SWAT-CUP (Abbaspour, 2015), specifically designed for the semi-automated calibration of SWAT outputs, was used for calibration and validation at the daily resolution, which is explained further in Section 4.5.

SWAT has a vegetated filter strip (VFS) function which was anticipated to be utilised for this study but was disregarded as this function has no impact on hydrology when the sub-watershed discretisation method is used (like in this study). The option of hillslope discretisation or grid cell discretisation (Arnold et al., 2012a) could allow detailed modelling of VFS in a specific sub-basin. This is achieved by routing flows from one land use (HRU) into another, rather than the sub-watershed discretisation method which sums each individual HRU for the sub-basin and routes to the channel (Arnold et al., 2012a). The common sub-watershed discretisation method was used in this study. The computational storage requirements for the alternative methods are extensive and these were disregarded as the aim of the study was to assess the overall impact of riparian buffer strips at upper, middle and lower catchment scales rather than at HRU and sub-basin scale. Ultimately, the hillslope discretisation and grid cell discretisation are useful for smaller sub-basin or HRU scale understanding of hydrology, which could be useful if comparing the field experiment outputs in this study to the modelled outputs, but this was beyond the scope of this study.

## 4.3 SWAT model setup

A baseline SWAT is setup using the sequential steps of: watershed delineation; HRU classification of soil, land use and slope; HRU analysis; and weather data processing. The following sections will outline the step-by-step process undertaken to set up SWAT for this study and identify input datasets for each stage of parameterisation. The HRU classification of land use was the mechanism used to create scenarios and will be outlined in Section 4.6. The input data and processes are outlined from Section 4.3.1 to Section 4.3.3. Data required for SWAT setup includes:

- Digital terrain model (DTM)
- GIS shapefile of river network (polyline)
- GIS shapefile of soils (polygon)
- GIS shapefile of land use (polygon)
- Weather data
    - Precipitation (daily and hourly), temperature (daily; minimum and maximum), relative humidity (daily), dewpoint (daily), wind speed (daily), and solar radiation (daily).

### *4.3.1 Weather data processing*

A key preparatory task for setting up SWAT is preparing the weather stations and their associated data for weather input files. These weather files are prepared as a time series and as averaged monthly weather statistics (for a minimum of 20 years of data). These monthly statistics are required to simulate weather for periods of no observed data and is a source of uncertainty (Arnold et al., 2012a).

**Time series data**

Aboyne weather station (Figure 4.2) data from 1994 to 2016 (daily and hourly time step) was obtained from the Met Office Integrated Data Archive System (MIDAS) Land and Marine Surface Stations Data (Met Office, 2012) hosted by the Centre for Environmental Data Analysis (CEDA) web processing service. Three substitute weather stations (Figure 4.2), sourced from Climate Forecast System Reanalysis (CFSR) databases (National Centres for Environmental Prediction, 2016), were used to fill missing daily data. Variable annual averages for each station were within 10% of one another and Aboyne. Additionally, Pearson correlation determined the relationship (and significance) of each variable between Aboyne and the CFSR stations. Table 4.1 outlines the variables utilised from each weather station, the number of days of missing Aboyne data that were replaced and their relevant correlations. The model was unable to process the weather data because Aboyne station was not within the catchment boundary. It was therefore moved 3.9 km east (Figure 4.2) to resolve the issue. Davoch precipitation data (JHI; See Section 3.3.3) was used to substitute 17 days of missing daily precipitation data in the Aboyne dataset (Table 4.1). These 17 days occurred from 22-26th December 2012 and 21 July 2016 to 1st August 2016. In preparing the precipitation data, a sequence to replace values was adopted:

i. Aboyne data was the primary data source;
ii. Where Aboyne precipitation data was missing, Davoch rainfall data would be sought first to replace the missing values;
iii. In the instance that both Aboyne and Davoch precipitation data was missing, the averaged CFSR precipitation would be used.

Table 4.1. Weather station data from Met Office Integrated Data Archive System (MIDAS) Land and Marine Surface Stations Data and Climate Forecast System Reanalysis (CFSR) databases used in SWAT data preparation. The number of missing input values for each input variable replaced by each type of substitute data are outlined and occurred in the model data period 01 January 1994 – 31 December 2016.

| *Aboyne (MIDAS station 150) weather variable* | *CFSR stations (573-31, 573-28 and 573-25) number of daily substitutes* | *Number of daily -99 values (to be estimated by monthly weather statistics)* | *Number of daily values replaced by Davoch rain gauge* | *Percent of Aboyne daily values (8401 total) replaced* |
|---|---|---|---|---|
| Precipitation (mm) | 145 | 0 | 17 | 1.9% |
| Wind speed (knots) | 107 | 14 | - | 1.5% |
| Minimum air temperature (°C) | 112 | 18 | - | 1.5% |
| Maximum air temperature (°C) | 112 | 15 | - | 1.5% |
| Mean air temperature (°C) | 0 | 130 | - | 1.5% |
| Relative humidity (as wet bulb temperature, decimal fraction between 0-1) | 137 | 12 | - | 1.8% |
| Dewpoint (°C) | 0 | 125 | - | 1.5% |
| Solar radiation (KJ/m2/day converted to MJ/m2/day) | 0 | 884 | - | 10.5% |

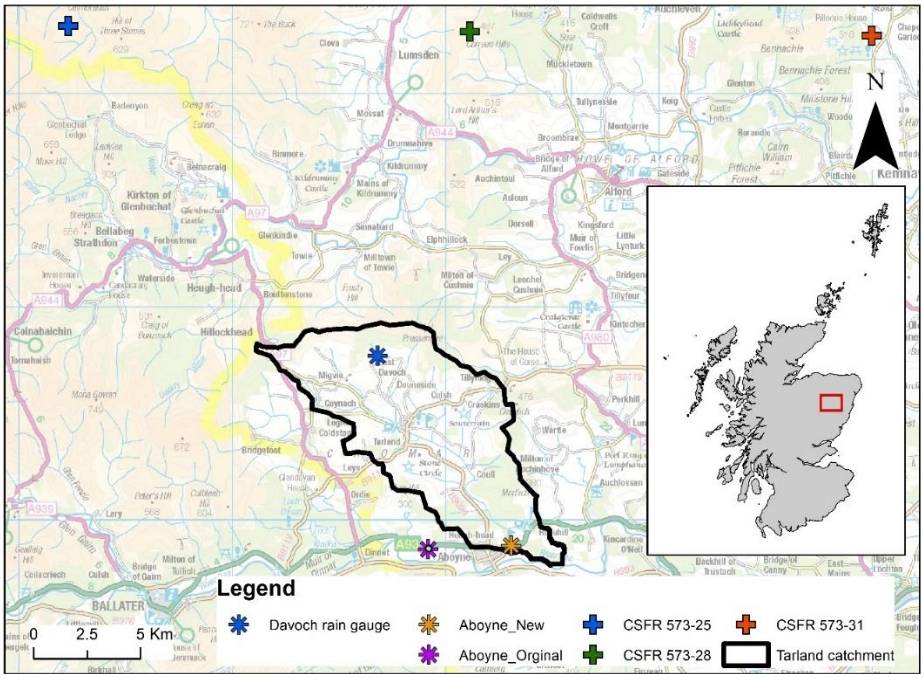



Figure 4.2. Location of weather stations from Met Office Integrated Data Archive System (MIDAS) Land and Marine Surface Stations Data and Climate Forecast System Reanalysis (CFSR) databases used for SWAT build.

Quality-controlled MIDAS data were used to reduce uncertainty. MIDAS wind speed values were converted from knots to m/s (where 1 knot = 0.514m/s) according to Met Office (2016) and relative humidity was converted from a percentage into a decimal fraction. As recognised by Met Office (2017a), where relative humidity was >100, (likely due to low temperatures) these were either replaced by averaged CFSR values or set to 100.

If any relative humidity values were <0, which can not occur, these values were replaced by CFSR data or where no other data existed, the default -99 value was used to prompt model simulation.

**Weather statistics**

Averaged monthly weather statistics for 1994 – 2016 were required in addition to the daily (or hourly precipitation) data (calculation and input values in Appendix 2). These statistics were utilised to estimate weather variables when data was missing (indicated using -99.0 value), which are identified in Table 4.1.

### *4.3.2 Watershed delineation*

A 1 m resolution DTM of the Tarland catchment and GIS shapefile of the stream network (Ordnance Survey, 2016) were required for watershed delineation. Two additional stream gauges were added to represent the location of Coull and Aboyne river gauge sites (Figure 4.3) to enable the use of observed data for calibration. An outlet was added to represent the experiment site to enable analysis of model performance at the field scale of the experiment site. The delineation process splits the catchment up into sub-basins based on the DTM by determining the lowest and highest points. There are 28 sub-basins in the Tarland catchment: sub-basin 17 represents the Coull gauging station and sub-basin 28 is the watershed outlet and represents Aboyne gauging station (Figure 4.3).

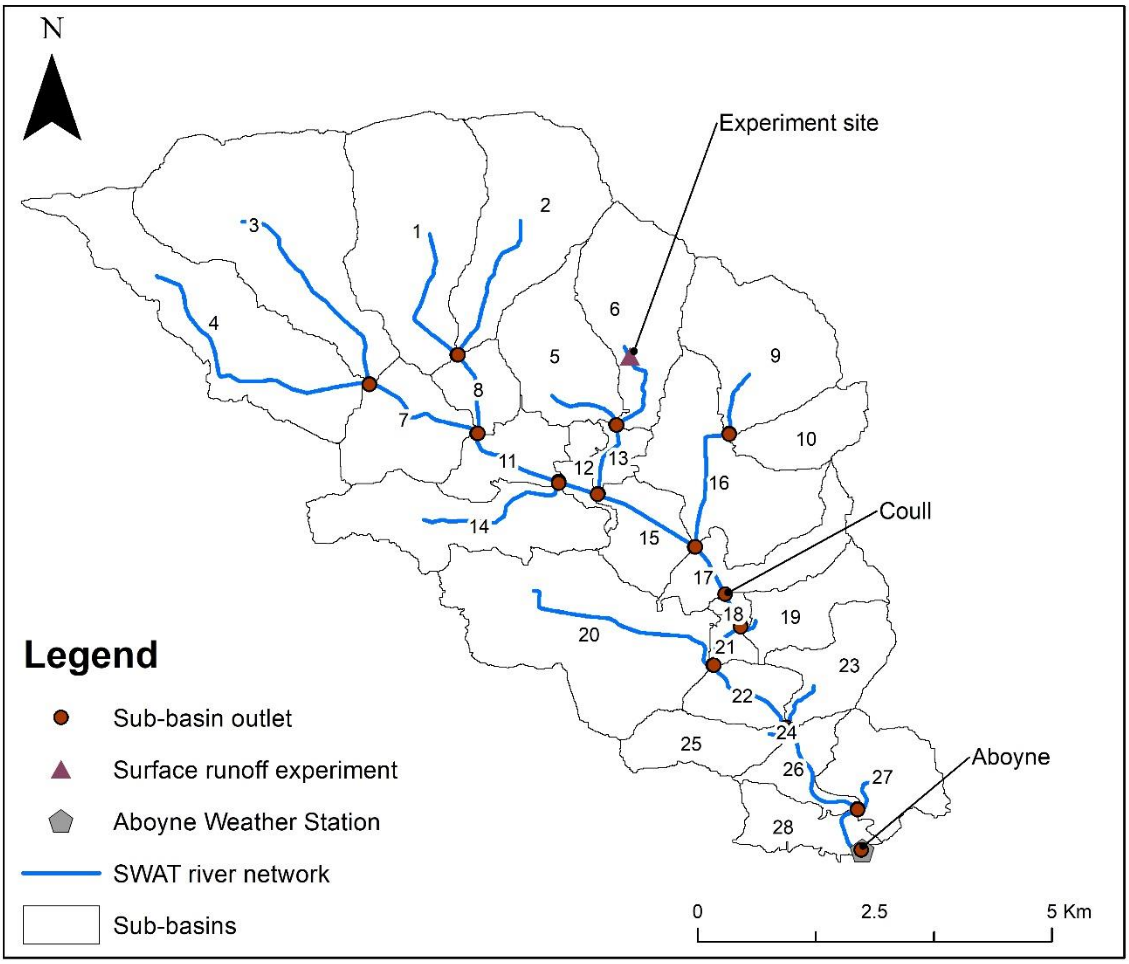



Figure 4.3. Watershed delineation of Tarland catchment including sub-basins and added outlets at Aboyne, Coull and the experiment site.

### *4.3.3 HRU analysis*

HRU definition requires land use data, soils data, and the definition of slope for the initial model setup. HRUs are effectively a smaller unit to the sub-basin and are broken down by the combinations of land use, soil and slope within the sub-basins.

**Land use**

The UK 2007 Land Cover Map (LCM) from the Centre of Ecology and Hydrology (CEH) (Morton et al., 2014) provided a 0.5 ha sale spatial distribution of land use across the Tarland catchment and descriptions in the attributes of each land use type (the latest 2015 dataset is not yet freely available). Each land cover was added to the SWAT database. The SWAT database contains a multitude of default values for example soils and land use types and their associated parameters values. These can be utilised where no information on parameters for a model exists or for any catchment in the United States (the model was developed in the United States). Users can otherwise input their own data to the database or derive parameters from closely related land uses or soils in the database.

The necessary parameter inputs (such as Leaf Area Index (LAI) and root depth) for each land use were not all available. Consequently, Tarland land uses were assigned to a suitably matching SWAT land use from the SWAT database (Appendix 3). The seven key SWAT land cover/plant descriptions (IDC) were assessed and matched to the LCM land uses that shared attributes. The IDCs used are shown in Table 4.2 but defined in Appendix 4 and were: trees, warm season annual, and perennial.

Table 4.2. Land use classifications for Tarland Land Cover Map (LCM) using SWAT land use database.

| *LCM 2007* | *Area ($km^2$)* | *SWAT Code* | *SWAT description* | *IDC* |
|---|---|---|---|---|
| Deciduous | 3.3 | FRSD | Forest Deciduous | Trees |
| Coniferous | 14.6 | FRSE | Forest Evergreen | Trees |
| Arable | 12.1 | AGRL | Agricultural land generic | Warm season annual |
| Improved | 20.6 | WPAS | Winter pasture | Perennial |
| Rough low productivity grassland | 4.2 | RNGE | Range grasses | Perennial |
| Acid grassland | 4.8 | WPAS | Winter pasture | Perennial |
| Heather dwarf shrub | 3.0 | RNGB | Range brush | Perennial |
| Heather grass | 5.7 | RNGB | Range brush | Perennial |
| Montane habitat | 0.03 | RNGE | Range grasses | Perennial |
| Lake | 0.3 | WATR | Water | n/a |
| Urban industrial | 0.2 | UIDU | Industrial | n/a |
| Suburban | 0.5 | URML | Residential medium/low density | n/a |

**Catchment soils**

A 1:25000 scale spatial representation of soils across the Tarland catchment was provided by JHI (2013). This dataset indicates each soil type, its drainage status and coverage area of the catchment. For each soil type, data on soil properties were provided by Dr. Allan Lilly from JHI. These soil properties originated as part of a study in which Dr. Allan Lilly co-authored (Boorman et al., 1995) to derive a hydrological classification of soil types in the UK called Hydrology of Soil Types (HOST). The data provided is outlined in Appendix 5, illustrating the soil property data required for SWAT and indicates the SWAT values derived using the HOST classification. HOST classifications are listed in (Appendix 6), including standard percentage runoff (SPR), for each soil series and identifies the hydrological group (HYDGRP) allocated by Lilly (2014).

**Slope definition**

Slope was determined using SWAT guidance (Arnold et al., 2012a). Slope statistics were calculated from the DTM. Guidance indicated the maximum percentage of slope should be divided by the number of elevation bands the user will adopt (a maximum of four). This value would determine the range of slope percentages per slope classes (as shown in Table 4.3). Slope classes can reduce the number of HRUs, allow derivation of slope specific parameters (e.g. increase runoff curve number) and dictates whether sheet flow may occur (Arnold et al., 2012a).

Table 4.3. Slope statistics and slope classes used in the model build as per guidelines of Arnold et al. (2012a)

| DTM derived slope statistics | | | |
|---|---|---|---|
| **Min** | 0 | **Maximum (used to divide by four slope classes)** | 72.1 |
| **Mean** | 11.5 | **Standard deviation** | 9.24 |
| **Slope classes used** | | | |
| | **1** | 18 | |
| | **2** | 36 | |
| | **3** | 56 | |
| | **4** | >56 | |

**HRU definition**

HRU definition allows the user to dictate the combinations that can be used to delineate the sub-basins into HRUs based on unique combinations of land use and soil types. This model used all combinations of land use and soils to enable the generation of runoff on a smaller scale. Allowing the dominant land use to classify the HRU would result in the riparian buffer scenarios being outweighed by other land uses and not considered in HRU or sub-basin calculations.

#### *4.3.4 SWAT warm up period*

The initial pre-calibration model setup used a three-year warm up period (for daily and hourly) to reduce the influence of initial conditions (e.g. the catchment may be particularly dry or wet). It was firstly run on a monthly time step from January 1994 to December 2016 and the water balance assessed. The subsequent daily time step was simulated and SWAT-CUP used for calibration and validation. Hourly calibration and validation were conducted manually following daily calibration.

## 4.4 Establishing return periods and high flow events

Calibration and validation required the analysis of observed data to determine high flow events, the return periods of these events and their distribution in each year of observation. This mitigated calibration to a particularly dry or wet year and SWAT simulations consequently being unable to be representative of high flow events.

Observed data for Coull from 2000-2016 was used to calculate AMAX and the median of AMAX (QMED). The method for determining the return period of peak flows was adopted from the Flood Estimation Handbook (FEH) method (Robson and Reed, 1999), which is a standardised approach in the UK. Extreme value analysis enables the determination of return periods for peak flows, which were used to identify high flow events in Coull observed flow data and compared to each modelled scenario. The FEH method for this analysis is to apply two forms of probability distribution function (PDF) curves to test the goodness of fit to flow data: Generalised Logistic distribution (GL) and Generalised Extreme Value distribution (GEV) (Robson and Reed, 1999). GL is shown in Equation 4.1 and GEV in Equation 4.2.

$$F\,(x) = \frac{1}{1 + e^{-w}}$$

Equation 4.1

Generalised Logistic (GL) cumulative distribution function (Chadwick, 2013)

$$F(x) = exp\left\{- \left[1 - \frac{k\,(x - \xi)}{\propto}\right]\right\}\, for\; k\ \neq 0$$

Equation 4.2

Generalised extreme value (GEV) probability distribution function (Maidment, 1993)

Where: ξ is a location parameter, α is a scale parameter and k is the shape parameter. In the process of generating the GL and GEV PDFs, L-moments (LMOM) statistical properties of the flow data were used to estimate the parameters of the growth curve using variance, covariance and skewness of the distribution (Robson and Reed, 1999). The resulting growth curves for Coull and Aboyne are exhibited in Figure 4.4. The 1 in 10 year was the highest return period used for assessing high flow events. As the Coull data series exists for 17 years and Aboyne for a 12-year period, the accuracy of estimating return periods beyond the 1 in 10 year would be uncertain.

The growth curves in Figure 4.4 show Coull observed data to be most aligned with the GL and GEV LMOM distributions and justified using observed data (from Coull rather than Aboyne) to determine the return period and percentiles (see Section 4.4.1) of high flow events. Using the GEV and GL methods, the peak flow for a 1 in 2, 1 in 5 and 1 in 10 year return period were determined for the daily and hourly data series (Table 4.4). To define and categorise high flow events, the return period and percentile flow values were utilised at Coull whereby the observed discharge would be ≥ peak flow (per return period) values (Table 4.4). Each of these events were compared when analysing model scenario outputs. The QMED, GL, and percentile peak flow values are highlighted in Table 4.4.

.

Table 4.4. Daily and hourly peak flow values for return periods using GEV and GL probability distribution functions, and percentiles. The QMED, GL and percentile flow thresholds were used to identify high flow events.

| | *Event type* | *Coull peak flow ($m^3/s$)* | | *Aboyne peak flow ($m^3/s$)* | |
|---|---|---|---|---|---|
| | | *Daily* | *Hourly* | *Daily* | *Hourly* |
| **Timeframe of data** | | Jan 1999 to Jan 2016 | | Mar 2003 to Mar 2016 | |
| | **QMED** | 4.99 | 6.07 | 6.34 | 9.08 |
| **GEV** | **1 in 2** | 5.14 | 6.26 | 6.54 | 9.37 |
| | **1 in 5** | 7.01 | 8.54 | 10 | 12.77 |
| | **1 in 10** | 8.12 | 9.88 | 10.32 | 14.78 |
| **GL** | **1 in 2** | 5.17 | 6.29 | 6.57 | 9.42 |
| | **1 in 5** | 6.86 | 8.35 | 8.72 | 12.49 |
| | **1 in 10** | 7.96 | 9.69 | 10.12 | 14.49 |
| **Percentile** | **Q30** | 5.38 | 7.10 | 8.31 | 11.44 |
| | **Q10** | 7.12 | 8.69 | 11.72 | 19.88 |

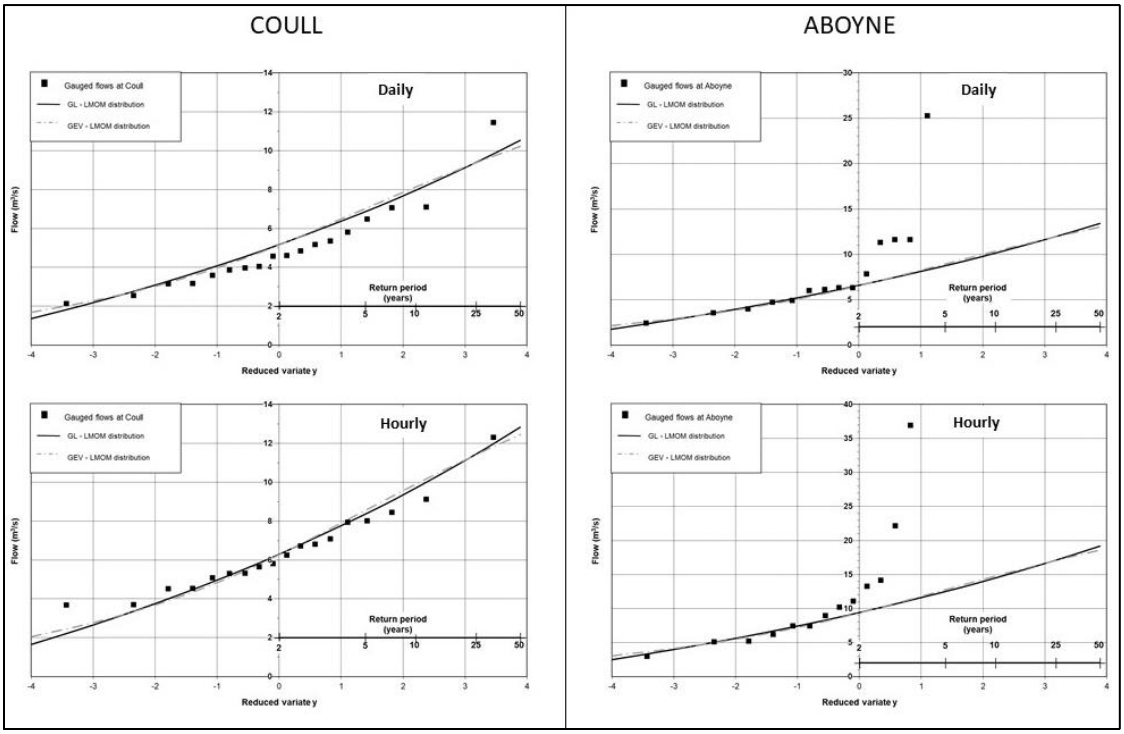



Figure 4.4. Daily and hourly growth curves for Generalised Logistic (GL) and Generalised extreme value (GEV) L-moments (LMOM) distributions for Coull and Aboyne. Daily and hourly derived QMED.

### *4.4.1 Percentiles*

To establish a threshold, percentile events and return periods defined the magnitude of high flow events. Percentiles of AMAX for Coull were calculated using Microsoft Excel to determine a flow threshold for 70$^{th}$ and 90$^{th}$ percentile (where high flow values occur 30% and 10% of the time (respectively), referred to herein as Q30 and Q10, consecutively). Coull was favoured in comparison to Aboyne to remain consistent with the derivation of return periods (Section 4.4). The Q30 and Q10 flow thresholds are outlined in Table 4.4. Thresholds of high flow events occurring between return periods were identified by percentiles. For example, the order of all high flow thresholds are as follows: QMED, 1 in 2, Q30, 1 in 5, Q10, and >1 in 10, respectively (Table 4.4).

### *4.4.2 Calibration and validation periods*

The methodology described for deriving return periods and percentiles determined calibration and validation periods shown in Table 4.5. Distinct years of observation were used for Coull and Aboyne in calibration and dictated by missing data at Coull, timeframes of observations at the gauges and careful consideration to calibrate to average hydrological conditions with respect to long term datasets. SWAT was first calibrated at daily resolution and subsequently at hourly resolution as it was anticipated validation parameters for daily may be adequate for hourly calibration. This was not the case, but some parameters applied at the daily resolution remained part of the hourly model setup and hence details for daily resolution calibration and validation are included here.

Table 4.5. Calibration and validation years for daily and hourly models.

| | ***Coull*** | | ***Aboyne*** | |
|---|---|---|---|---|
| | ***Calibration*** | ***Validation*** | ***Calibration*** | ***Validation*** |
| Daily | 1999-2001 | 2010-2012 | 2005-2007 | 2010-2012 |
| Hourly | 2014 | 2012 | - | - |

By assessing the number of events and the event types (as per return period or percentile event) in each year of observed data, calibration and validation years were selected (for daily and hourly separately). Aboyne and Coull were calibrated at daily resolution; whereas only Coull was calibrated at hourly resolution. This was partly due to the manual approach to calibration for hourly which allowed for calibration at one station at a time only; whereas daily could be achieved simultaneously (see Appendix 7). There was greater confidence in the Coull observed data (Aboyne station changed ownership part way through the data series and calibration regime is unknown). This confidence in Coull over Aboyne observations was evident during calibration at hourly resolution. Aboyne was therefore compared at hourly resolution during calibration and validation but was not a principle focus.

## 4.5 SWAT-CUP

SWAT-CUP was utilised to calibrate the daily resolution model but not the hourly. The statistics and goodness-of-fit were insufficient at the hourly resolution in SWAT-CUP and thereby prompted a manual approach which is demonstrated in Table 4.7. The daily calibration was conducted first, and these values applied to the hourly model prior to manual calibration. Details on calibration, validation and sensitivity analysis in SWAT-CUP at daily resolution are provided in Appendix 7.

Table 4.6. Daily calibration parameterisation and parameter sensitivity. Includes global analysis statistics and determines whether one-at-a-time (OAT) sensitivity showed change to flow. Final fitted values for daily model are highlighted under Iteration 1. Refer to Appendix 7 for details.

| | | | ***Iteration 1*** | | | ***Sensitivity analysis*** | | |
|---|---|---|---|---|---|---|---|---|
| ***Parameter*** | ***Description*** | ***Operator*** | ***Min*** | ***Max*** | ***Fitted values*** | ***OAT*** | ***Global: t stat*** | ***Global: P-value*** |
| CN2 | SCS runoff curve number for moisture condition | Multiply | -0.2 | 0.2 | -0.191833 | | -3.11 | 0.000 |
| SOL_AWC (mm/mm) | Available water capacity of all soil layers | Multiply | -0.2 | 0.4 | 0.045 | | 1.25 | 0.029 |
| SOL_K (mm/hr) | Saturated hydraulic conductivity | Multiply | -0.8 | 0.8 | 0.461333 | | 0.21 | 0.005 |
| ESCO | Soil evaporation compensation factor | Replace | 0 | 1 | 0.548333 | | 0.22 | 0.044 |
| EPCO | Plant uptake compensation factor | Replace | 0 | 1 | 0.591667 | No change | -0.50 | 0.450 |
| GWQMN (mm) | Threshold depth of water in the shallow aquifer required for return flow to occur | Replace | 0 | 500 | 474.166656 | No change | 1.47 | 0.111 |
| ALPHA_BF (days) | Baseflow alpha factor | Replace | 0 | 1 | 0.958333 | | -5.81 | 0.000 |
| GW_DELAY (days) | Threshold depth of water in the shallow aquifer required for return flow to occur | Replace | -30 | 120 | 19.75 | | 12.14 | 0.000 |
| OV_N | Manning's "n" value for overland flow | Multiply | -0.3 | 3 | 1.6745 | | 1.84 | 0.000 |
| REVAPMN (mm) | Threshold depth of water in the shallow aquifer for "revap" to occur | Replace | 10 | 500 | 162.71666 | No change | -0.55 | 0.978 |
| CH_K2 (mm/hr) | Effective hydraulic conductivity in main channel alluvium | Multiply | -0.6 | 0.6 | -0.382 | No change | 1.50 | 0.737 |

Table 4.7. Hourly model parameterisation using manual calibration. Green coloured rows indicate parameters changed when assessing the overall water balance.

| *Parameter* | *Definition* | *Operator* | *Parameter change/value* |
|---|---|---|---|
| GW_DELAY.gw (days) | Groundwater delay. | Replace | 20 |
| ALPHA_BF.gw (days) | Baseflow alpha factor. | Replace | 0.5 |
| GWQMN.gw (mm) | Threshold depth of water in the shallow aquifer required for return flow to occur. | Replace | 600 |
| GW_REVAP.gw | Groundwater "revap" coefficient. | Replace | 0.05 |
| REVAPMN.gw (mm) | Threshold depth of water in the shallow aquifer for "revap" to occur. | Replace | 300 |
| OV_N.hru | Manning's "n" value for overland flow. | Replace | Values replaced as per allocation to land use type. See Appendix 8 |
| ESCO.hru | Soil evaporation compensation factor. | Replace | 0.25 |
| EPCO.hru | Plant uptake compensation factor. | Replace | 0.25 |
| CN2.mgt | SCS runoff curve number for moisture condition. | Multiply | i. apply daily changes<br>ii. all values >50 multiply by 0.65<br>iii. all values multiply by 1.332 |
| SOL_AWC.sol (mm/mm) | Available water capacity of the soil layer. | Multiply | i. apply daily changes<br>ii. multiply all values by 2.75<br>iii. multiply all values by 1.5 |
| SOL_K.sol (mm/hr) | Saturated hydraulic conductivity. | Multiply | i. apply daily chnages<br>ii. multiply all values by 1.75<br>iii. multiply all values by 3.747978 |
| CH_N2.rte | Manning's "n" value for the main channel. | Replace | 0.225 |
| CH_K2.rte (mm.hr) | Effective hydraulic conductivity in main channel alluvium. | Multiply | apply daily changes |
| CH_N1.rte | Manning's "n" value for tributary channels. | Replace | 0.1 |
| SFTMP.bsn | Snowfall temperature. | Replace | 0 |
| SMTMP.bsn | Snow melt base temperature. | Replace | 2 |
| SMFMX.bsn | Maximum melt rate for snow during year (occurs at summer solstice). | Replace | 2 |
| SMFMN.bsn | Minimum melt rate for snow during the year (occurs at winter solstice). | Replace | 2 |
| EPCO.bsn | Plant uptake compensation factor. | Replace | 0.95 |
| SURLAG.bsn | Surface runoff lag time. | Replace | 2 |

### *4.5.1 Sensitivity analysis*

Each parameter in Table 4.7 (except those coloured green) and Table 4.8 was manually changed to a very high and a very low value based on its absolute minimum and maximum values outlined by the SWAT database. This enabled a better understanding of how each parameter influenced the simulated flow; enabling a suitable value to eventually be determined. The most sensitive parameters are highlighted in yellow in Table 4.8: CN2, SOL_AWC, SOL_K and CH_N2 (defined in Table 4.7).

Table 4.8. Hourly manual parameter sensitivity test findings with sensitive parameters highlighted in yellow.

| ***Parameter*** | ***Sensitivity description*** |
|---:|---|
| GW_DELAY.gw (days) | Kept similar value to daily as made no difference to baseflow |
| ALPHA_BF.gw (days) | Reduced but made limited difference to baseflow |
| GWQMN.gw (mm) | Halved this value to amend the smoothed baseflow |
| GW_REVAP.gw | Halved this value to amend the smoothed baseflow |
| REVAPMN.gw (mm) | Value doubled: made minor change to instantaneous rainfall response by peaks |
| OV_N.hru | Manually amended to reflect land uses but made no difference to flow output |
| ESCO.hru | Reduced but made no difference to output |
| EPCO.hru | Reduced but made no difference to output |
| CN2.mgt | Reduced by 75%, lowering peaks slightly and reducing baseflow |
| SOL_AWC.sol (mm/mm) | Increased values; highly responsive as peak timing was shifted |
| SOL_K.sol (mm.hr) | Increased values significantly which picked up smaller peaks better |
| CH_N2.rte | Peaks highly responsive |
| CH_K2.rte (mm/hr) | Increased values by 75% but made no difference |
| CH_N1.rte | Made no difference with any change to values |

### *4.5.2 Calibration and validation output analysis*

To remain consistent with the daily calibration process conducted in SWAT-CUP, NS and $R^2$ were the objective functions when calibrating the hourly outputs to Coull. Details on NS and $R^2$ objective functions are provided in Appendix 7 where the calculations are outlined for daily calibration. The best simulations were graphed against the Coull observations to illustrate goodness-of-fit and are presented in Chapter 6.

## 4.6 Scenarios

To address RQ3, the model scenario outputs were assessed against their impact on Ttp, Qpk and volume of runoff. These parameters were assessed to provide an understanding of whether the buffer strip scenarios attenuated peak flows (e.g. Ttp), reduced Qpk or increased catchment storage by reducing runoff volumes. The impact of each scenario on these parameters was examined in the upper catchment (Netherton), middle catchment (Coull) and lower catchment (Aboyne) to understand the spatial scales of effectiveness. The scenarios (shown in Table 4.9) tested were:

- Varying widths (10 m, 20 m, 30 m and 50 m) of catchment-wide implemented riparian buffer strips to ascertain the most effective width at reducing Ttp, Qpk and runoff volume.
- Grass-based and tree-based buffer strips applied to each buffer width scenario. This would determine whether the vegetation type influenced the effectiveness of buffer width in reducing Ttp, Qpk and runoff volumes.
- An approximate equivalent area of the 50 m tree-based buffer scenario redistributed to steeper sloped land (hillslope scenario) and replacing land uses that are likely to be less intensively managed (acid grassland and heather grassland) with deciduous trees. The purpose of this was to compare to the 50 m tree-based buffer and:

- Establish whether the location of the ‘buffer strip’ altered the impact on Ttp, Qpk and runoff volume; and
- Determine whether replacing different types of land use (from those replaced by the 50 m buffer scenario), on different soil types, with the tree-based scenario, influenced the Ttp, Qpk and runoff volume.

The implementation of the buffer strip scenarios indicated that intensively managed agricultural land, likely of high economic value, was the most common land to be replaced when the buffer width was increased. This forms the rationale for the hillslope scenario which aims to understand whether replacing less intensively managed (and less economically viable) land on steeper slopes would have the same or a different impact on Ttp, Qpk and runoff volume. Based on previous research (McLean et al., 2015), land managers are more inclined to plant trees on land that is less economical for their business.

Table 4.9. Modelling scenarios tested, and variables analysed for each event.

| ***Scenarios*** | | ***Variables*** | ***Events*** |
|---|---|---|---|
| • Existing buffers (baseline)<br>• Catchment wide buffers<br>  ○ 10 m<br>  ○ 20 m<br>  ○ 30 m<br>  ○ 50 m<br>• 50 m buffer redistributed to hillslopes | • Grasses<br>• Deciduous trees | • Time to peak (Ttp)<br>• Peak (Qpk)<br>• Volume runoff (mm) | • QMED<br>• 1 in 2 year<br>• Q30<br>• 1 in 5 year<br>• Q10<br>• 1 in 10 year |

### *4.6.1 Riparian buffer strip scenario build*

A twin-approach was used to incorporate existing riparian buffer strips into the baseline model and ensure they were representative. A study by  Cooksley et al. (2011) outlined the sequential implementation of the riparian buffer strips according to previous works carried out in Tarland catchment. This was a simplified map, however and required more specific spatial representation. A further study carried out by JHI internal use mapped existing buffer strips using satellite images of Tarland catchment. Using a combination of both, enabled a more spatial and temporal representation of riparian buffer strip implementation. Only buffer strips which overlapped between these two studies were considered for use in the baseline model of this study, as clarification the buffers exist in their respective locations and timing of their implementation. Based on this approach, Table 4.10 shows a timeline of implementation and the area of land converted to riparian buffer strip. Further details of incorporating the riparian buffer strips into the land use data is covered in HRU analysis in Section 4.3.3.

Table 4.10. Area of land converted to riparian buffer strip over time

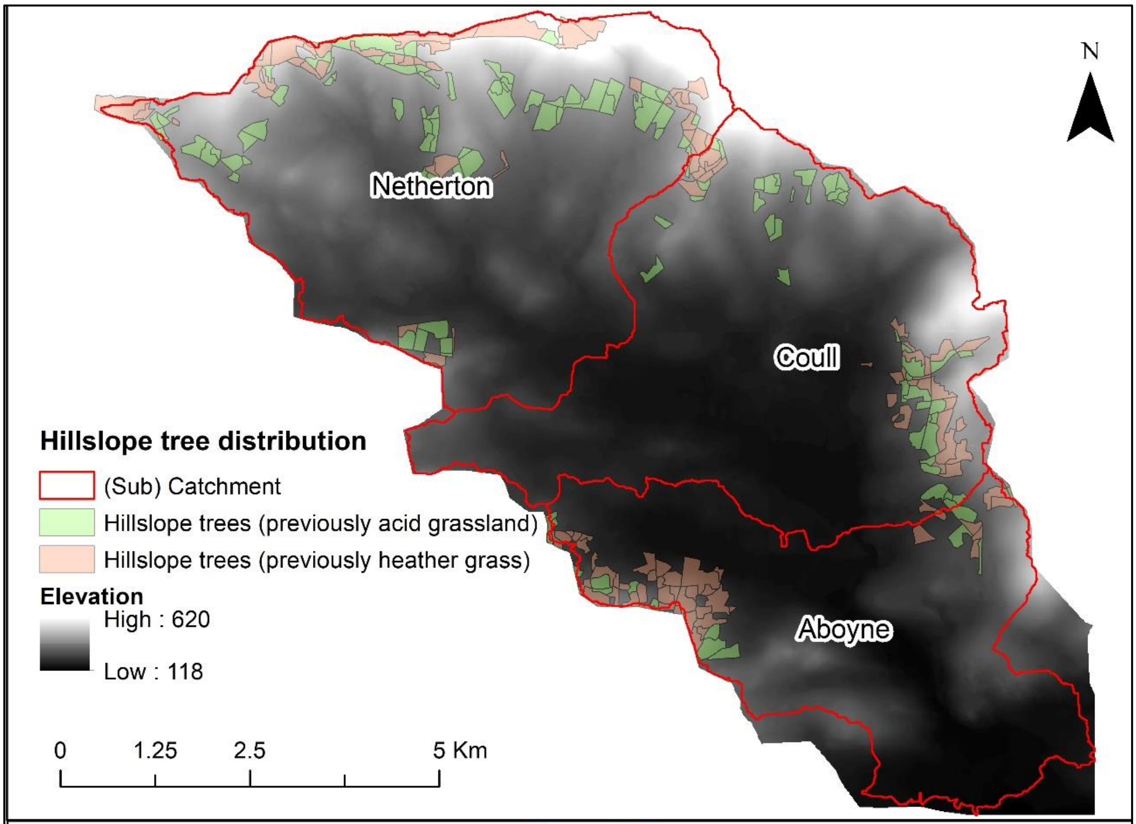
| ***Year*** | ***Area of riparian buffer strip implemented (km$^2$)*** | ***% area of catchment (73 km$^2$)*** |
|---|---|---|
| Pre 2000 | 0.003 | 0.004% |
| 2001 | 0.003 | 0.004% |
| 2003 | 0.002 | 0.003% |
| 2005 | 0.045 | 0.062% |
| 2006 | 0.005 | 0.007% |
| 2009-10 | 0.035 | 0.048% |
| *Total* | 0.093 | 0.127% |

The land use scenario input files were prepared using ArcGIS to create a buffer of the relevant width adjacent to the river network. This buffer area spatially replaced existing LCM2007 land uses underlying the buffer area. These were subsequently classified as specific land use types, which would specify the vegetation type (grasses or deciduous trees).

A separate model was set up for each riparian buffer width scenario and the hillslope scenario, which was necessary because changing the spatial distribution of land uses could not be achieved through other model editing avenues. Each model was set up using the same protocol (as described in Section 4.3 and 4.5) but with different land use input files implemented.

### *4.6.2 Hillslope scenario build*

The spatial distribution of riparian buffer strips is inherently adjacent to watercourses, but the topography and soils are likely to have an influence on how effective vegetation can be at reducing flood hazard. As described in Section 4.6, the 50 m wide tree buffer scenario was approximately redistributed onto steeper land consisting of acid grassland and heather grassland, replacing them with deciduous trees (Figure 4.5).



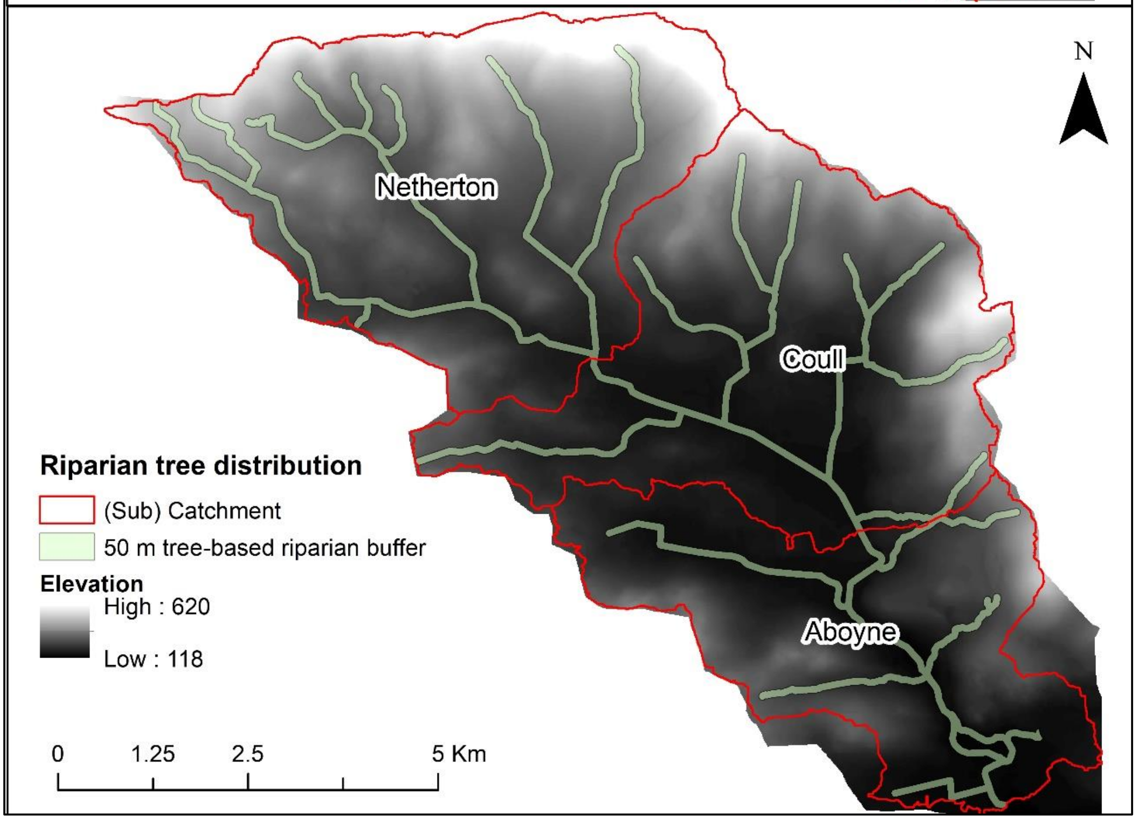




Figure 4.5. Elevation and location of hillslope trees (which replaced acid grassland and heather grassland land uses, top picture) and riparian trees (lower picture).

The locations of the hillslope trees (Figure 4.5) were selected based on a visual assessment in ArcGIS and included the following steps:

- Determine land uses that would have less agricultural productivity and thereby more likely to adopt tree planting. These were: heather grassland, acid grassland and rough low-productivity land.
- Using the DTM, ascertain which of the three shortlisted land uses covered steeper land. Rough low-productivity land was excluded at this point as it was situated in lower elevations
- Select acid grassland and heather grassland land parcels in the LCM shapefile that overlay the steep land and change the properties to reflect deciduous trees.
- Create another SWAT model (as per Section 4.3) using the new LCM land classifications for hillslope trees, apply calibration parameters (Table 4.6 and Table 4.7) and run the model.

### 4.7 Model output analysis

To enable better understanding of subsequent model output results, statistics on the conditions of each event and the spatial distribution of land uses and soils in each sub-catchment was required. Comparisons between scenarios and their impact on Ttp, Qpk and volume of runoff were conducted by assessing percentage reductions at different spatial scales at the upper catchment (Netherton), middle catchment (Coull), and lower catchment (Aboyne). Outputs for grass-based buffer strips and tree-based buffer strips were also compared. The purpose of each analysis factor is outlined in Table 4.11 and described in more detail in the following sections.

Table 4.11. Variables for event conditions, spatial distributions and flow responses analysed for each high flow event, and the purpose of including these variables in the analysis.

| | ***Condition/Characteristic/Response*** | ***Purpose*** |
|---|---|---|
| Event conditions | Pcp depth | To understand any relationship between antecedent conditions or rainfall event characteristics and flow conditions. Assesses likelihood of reductions in Ttp, Qpk and runoff volume being due to rainfall characteristics or API30. |
| | Event duration | |
| | Pcp intensity | |
| | API30 | |
| Spatial distributions | Area of land covered by each scenario | Like event conditions, the coverage of land use types (and how they change with each buffer scenario) being replaced over underlying soil distributions may be an influencing factor on why flow responses change. As the buffer scenarios consist of grass and trees, this assessment will provide overview of increasing/ decreasing coverage of grasses and trees, which may affect hydrology. |
| | The area of each of the different land uses that were replaced by each scenario | |
| | The areas of all land use types for each scenario | |
| | The coverage of each soil type | |
| | The area of each soil type covered by the 50 m riparian tree buffer scenario and the hillslope tree scenario. | |
| Flow responses | Ttp | Important variables to assess the impact of the scenarios implemented in conjunction with the range of event conditions and spatial distributions of land uses and soils. Ttp considers whether the peak has been delayed. Qpk examines the peak flow and whether that has been reduced. Volume of runoff indicates the degree of additional water storage in the catchment. |
| | Qpk | |
| | Volume of runoff | |

### *4.7.1 Event conditions*

A high flow event is defined when precipitation begins followed by a rise in flow in response to it (peaking to above QMED i.e. bankfull) and concludes when the flow returns to pre-event values. The event begins when the precipitation begins to ensure event condition calculations reflect a realistic volume of precipitation and event characteristics. For each high flow event identified using the method in Section 4.4, of which there are 21 events, the following event characteristics were calculated: pcp depth (mm), event duration (hr), pcp intensity (mm/hr), and the antecedent conditions, API30 (mm). The method for calculating these are described in Table 4.12.

Table 4.12. Methods for calculating event conditions.

| *Event characteristic* | *Method of calculation* |
|---|---|
| Pcp depth | Sum of precipitation for each high flow event |
| Event duration | Count of hours from start to end of high flow event |
| Pcp intensity | Pcp depth divided by event duration |
| API30 | Calculated using the method outlined in Chapter 3 (Section 3.3.4) |

### *4.7.2 Spatial distributions*

Ascertaining the areas of land that are changed by implementing each scenario is essential to understanding later results about the reduction in Qpk and volume of runoff. The land use type of the area 'lost' to the implemented buffer strip scenarios may influence the degree of reduction in Qpk and volume of runoff to a greater or lesser extent. This included using ArcGIS spatial analyst, spatial joins and geometry tool to calculate the following (per sub-catchment and at catchment scale):

- The area of land covered by each scenario
- The area of the different land uses that were replaced by each scenario
- The areas of all land use types for each scenario
- The coverage of each soil type
- The area of each soil type covered by the 50 m riparian tree buffer scenario and the hillslope tree scenario.

### *4.7.3 Time to peak*

For each of the twenty-one high flow and return period events, an event number was attributed to the peak flow in the timeseries and a number attributed to every (hourly) timestep of the model outputs. These were consistent for all stations and for all events. Each of the high flow events were graphed and the start of an event was visually identified at the first timestep where the flow began to continually rise prior to reaching the peak flow. Using a Microsoft Excel macro, (for each event) the timestep number of the beginning time step was then subtracted from the timestep number of the peak (+1) to define the number of hours from the start of the event until the peak flow of the event. This was then compared to the Ttp for each event calculated for the baseline flows.

### *4.7.4 Peak flow*

For each event, Qpk was identified for the calibrated baseline model and each of the scenario outputs at each of the catchment scales (upper, middle, and lower). The %↓Qpk from the baseline model and for each scenario was then calculated. These values were displayed as a boxplot, created in Minitab, to clearly show the range of percentage Qpk reductions per scenario and at the different spatial scales of each sub-catchment (Netherton, Coull, and Aboyne). The %↓Qpk for each event was summarised per scenario and per sub-catchment into descriptive statistics (average, minimum, maximum, and median) to provide a broader picture of the overall response to all events.

The impact of the tree buffer scenarios on Qpk compared to the grass buffer scenarios was examined by subtracting the percentage reduction in Qpk for grasses from the trees, for all scenarios. This would illustrate (by means of negative values) whether grasses had a greater reduction impact on Qpk than trees.

The hillslope tree scenario was compared to the 50 m tree buffer scenario in terms of their percentage reduction in Qpk. The average of the percentage reduction in Qpk for all events were compared for both scenarios at all spatial scales.

#### 4.7.5 Volume of runoff

The methodology for assessing the impact of scenarios on Qpk was also used for volume of runoff, primarily to establish the degree of catchment storage and whether this coincided with reductions in Qpk.

Volume of runoff was calculated by:

$$V_r = \int Qta$$

Equation 4.3

Where: $V_r$ is the volume of runoff, $Q$ is discharge, $t$ is time, $a$ is catchment area. The volume of runoff (mm) is for the area of the catchment. Volume was calculated for high flow events (defined in Section 4.7.1) for each scenario.

#### 4.7.6 Correlation to event conditions

To ascertain any relationships with event conditions, the percentage reduction in Qpk was assessed using Pearson correlation in Minitab against all the event condition statistics (Section 4.7.1). The same test was carried out between volume of runoff and event conditions. This test would provide insight as to whether the catchment antecedent conditions or the event characteristics has a relationship with the percentage reduction in Qpk and volume of runoff. Furthermore, these results will allow an additional assessment of each scenario’s ability to reduce Qpk or volume of runoff alongside an understanding of underlying soils and land uses distributions.

### 4.8 Uncertainty

Modelling is inherently uncertain because of the accumulation of errors in inputs, assumptions, calculations and outputs. These errors may also derive from extrapolating existing data as well as data predictions from other models. It is imperative to understand and be explicit about the sources of these uncertainties and take measures where possible to reduce uncertainty. Where uncertainty cannot be reduced, being explicit about where they occur enables future users of a model to take this into account and understand the constraints of model outputs (Beven, 2007).

In building SWAT for the Tarland catchment the following uncertainties and errors should be acknowledged for the input data:

- Aboyne weather station may not be representative of other locations in the catchment. For example, Aboyne is situated in the lower catchment at an elevation of 140 mAOD; whereas the highest elevation in the catchment is 620 mAOD.
- Precipitation data could be underrepresented due to wind-induced under catch (Pollock et al., 2018).
- The rating curve applied to river stage data Netherton, Coull and Aboyne gauging stations is an estimation and changes over time as the channel form changes, which can result in under or over estimation of flows. The reliability of this estimation is dependent upon regular calibration. The channel at Coull was dredged in October 2013 which would have altered the rating curve estimation and hence calibration and
- validation years prior to this were used. Errors in observed data has a knock-on effect on model uncertainty as models assume observations have no errors (Beven, 2012) and SWAT (hourly) was calibrated and validated to the observed Coull flows.

CEDA weather data is recognised to have a resolution of accuracy for the data utilised from the Aboyne station (Met Office, 2017a), which is outlined in Table 4.1:

- The LCM2007 dataset is out of date and may not be fully representative of the catchment (The LCM2015 dataset has been published but incurs a licence fee and was unable to be obtained). With 83% accuracy (tested over 9127 ground sites across the UK), the resolution for this data is 0.5 ha and any linear elements <20 m wide were incorporated into other features (CEH, 2011).
- Representation of existing riparian buffer strip was established using JHI unpublished internal work derived from aerial photography in 2015 combined with the identification of buffer implementation sites from Cooksley et al. (2011). Spatial inaccuracies may affect the exact location of existing buffer strips.
- Soils data was obtained from JHI and were attributed soil property attributes using HOST by one of its authors, Dr. A Lilly (Boorman et al., 1995). A degree of subjectivity from professional expertise and 1 km resolution may not be fully representative of the catchment. The soils input data was highly detailed but there are uncertainties in their distribution and the estimation of the parameters that are intrinsic to HOST (Boorman et al., 1995)

As well as uncertainty for the datasets utilised to develop the Tarland SWAT model, SWAT had its own uncertainties that should be acknowledged for this study. These uncertainties include:

- Utilising the estimation of missing weather data from monthly weather statistics are inherently uncertain and can influence flow values by misrepresenting precipitation inputs and water losses through evaporation or aquifer recharge. The use of these values in the calibration and validation period may have resulted in parameterisation errors when optimising peak flow representation.
- Using default values for land uses may not be representative.

- HRUs are assumed to respond homogenously when their response may be heterogeneous despite having the same land uses, soils and slope. These may be influenced by local scale land management practices at a high resolution.
- The objective functions utilised for calibration (NS and $R^2$) has been criticised by Beven (2012) as leading to biased parameter estimates. NS can have its largest errors at the hydrograph peaks, which can result in peak flows being given a greater weighting in parametrisation than low flows (Beven, 2012). However, this study is focused primarily on the reduction in flow peaks and thereby calibrating in a manner to replicate these peaks as closely as possibly will enable an improved estimation of reduction in peak flows.
    - Sensitive hourly model parameters (CH_N2 and CH_K2) are estimates and not based on any observational data. Uncertainty in their values and influence of equifinality is a limitation.
- Manual calibration at hourly resolution does not have equivalent uncertainty analysis as using SWAT-CUP, which was, in any case, unable to represent the observations sufficiently.
- There is an element of user uncertainty for hydrological models where errors may occur without the user being aware or able to mitigate.
- Although the soils input data was highly detailed, there are uncertainties in their distribution and the estimation of the parameters that are intrinsic to HOST
- The manual parameter changes to CN2 (the SCS runoff curve) due to SWAT-CUP taking the suggested parameter range out with the minimum and maximum threshold for CN2 are estimates and may not be representative.

## 4.9 Chapter summary

This chapter has introduced SWAT and outlined the required data inputs and model setup processes required to establish the Tarland SWAT model. Derivation of return period and percentile events for Coull were described and uncertainties in the observed data identified. Calibration and validation processes using SWAT-CUP for the initial daily model setup were mostly unable to be translated into the hourly model and required manual calibration and validation at hourly resolution. Sensitivity of parameters in SWAT-CUP and in the manual approach highlighted the most sensitive parameters which differed for daily and hourly resolution.

Methods for analysing SWAT outputs highlighted the use of event conditions (e.g. antecedent conditions, precipitation depth, event duration and intensity), Ttp, peak flows and volume of runoff to ascertain the most effective riparian buffer strip scenario for reducing flood hazard. SWAT was utilised as a tool to estimate the impact of catchment-wide riparian buffer strip on reducing flood hazard and ascertain the most effective buffer width and vegetation. However, uncertainties in model inputs and outputs are indicated to enable transparency in the effectiveness of the model predictions.

# Chapter 5 Experimental results

## 5.1 Chapter introduction

This chapter presents the results which inform the field scale aspect in the assessment of riparian buffer strips and their influence on multiple ES (Figure 1.1, page 4). The results from the surface runoff experiment provide an indication of runoff attenuation exerted by the riparian buffer strip, which indicates the degree of flood regulation (Figure 1.1) and answers RQ1. The overall condition of nutrient cycling and primary production (supporting ES) are compared between a buffered and non-buffered site and are determined by ecological quality. The results for the supporting ES experiments address RQ2. At field scale, these results will inform discussion (in Chapter 7) as to whether riparian buffer strips are an effective NFM measure by providing multiple ES (nutrient cycling and primary production), including flood regulation.

## 5.2 Research question 1 results: introduction

*RQ1: What are the different conditions by which overland flow moves into and through riparian buffer strips?*

The results in the following sections pertaining to RQ1 will break down the RQ and answer each element in turn. Firstly, the land management observations and categories will be outlined. Overland flow type is then defined for runoff events based on soil infiltration rates. The results from the delineation of the 95$^{th}$ percentile rainfall events (Q5 events) into infiltration, runoff or rejected events are then presented. These events are attributed to their respective statistics for the event conditions (e.g. pcp depth, and duration) and the experiment variables (e.g. soil VWC peak, runoff flow peaks, and the contributing area of runoff).

The results then set out the findings predominantly for the runoff events, including the event conditions (e.g. precipitation depth and antecedent conditions) and the influencing factors (e.g. land management and seasonal event conditions). These aspects address the *different conditions by which overland flow moves into and through riparian buffer strips* (RQ1). However, it is pertinent to understand the conditions when infiltration occurs, (but runoff does not) to highlight any additional conditions where runoff events occur. Furthermore, results compare the runoff events per land management type and seasonal event conditions to ascertain the combination of conditions where runoff is exacerbated. Results are supported by additional field observations obtained during high flow events where the monitoring equipment had failed.

### *5.2.1 Land management observations*

The land use management categories are used for analysis of influencing factors when examining distinctions between runoff and infiltration events. They will contribute to understanding the conditions in which overland flow moves into the riparian buffer strip (RQ1). The conditions for each land management category are explained in Table 5.1 and illustrated using photographs in Figure 5.1. Monthly photographs of land use management were summarised in two ways:

- Upslope categories: eleven categories (Table 5.1) stipulating the land management activity in the field immediately adjacent to the experiment site as well as upslope.
- Adjacent field categories: eight categories for the adjacent field only (Table 5.1).

The adjacent field was characterised by a perimeter zone, parallel to the riparian buffer strip, often a different crop from that situated in the centre of the adjacent field (Figure 5.1). However, when the adjacent field was *short crop* (adjacent category A5,Table 5.1) and *tall crop* (adjacent category A6, Table 5.1 and Figure 5.1) this perimeter did not exist.

Table 5.1. Land management classification definitions. Refer to Figure 5.1 for pictorial representations.

| ***Upslope category*** | ***Upslope fields*** | ***Adjacent field*** | ***Adjacent category*** | ***Adjacent field*** |
|---|---|---|---|---|
| **U1** | 5 fields bare soil; 1 field short crop | short crop perimeter; bare soil centre | **A1** | short crop perimeter; bare soil centre |
| **U2** | 5 fields bare soil; 1 field short crop | bare soil | **A2** | bare soil |
| **U3** | all short crop | short crop perimeter; bare soil centre | **A3** | tall crop perimeter; swede growth centre |
| **U4** | 5 fields tall crop; 1 field short crop | tall crop perimeter; swede growth centre | **A4** | short crop perimeter; swede growth centre |
| **U5** | all short crop | short crop perimeter; swede growth centre | **A5** | all short crop |
| **U6** | 2 fields bare soil; 4 fields short crop | short crop perimeter; swede growth centre | **A6** | Tall crop |
| **U7** | 5 fields bare soil; 1 field short crop | short crop perimeter; swede growth centre | **A7** | No data |
| **U8** | 2 fields bare soil; 4 fields short crop | bare soil | | |
| **U9** | all short crop | all short crop | | |
| **U10** | tall crop | tall crop | | |
| **U11** | no data | no data | | |

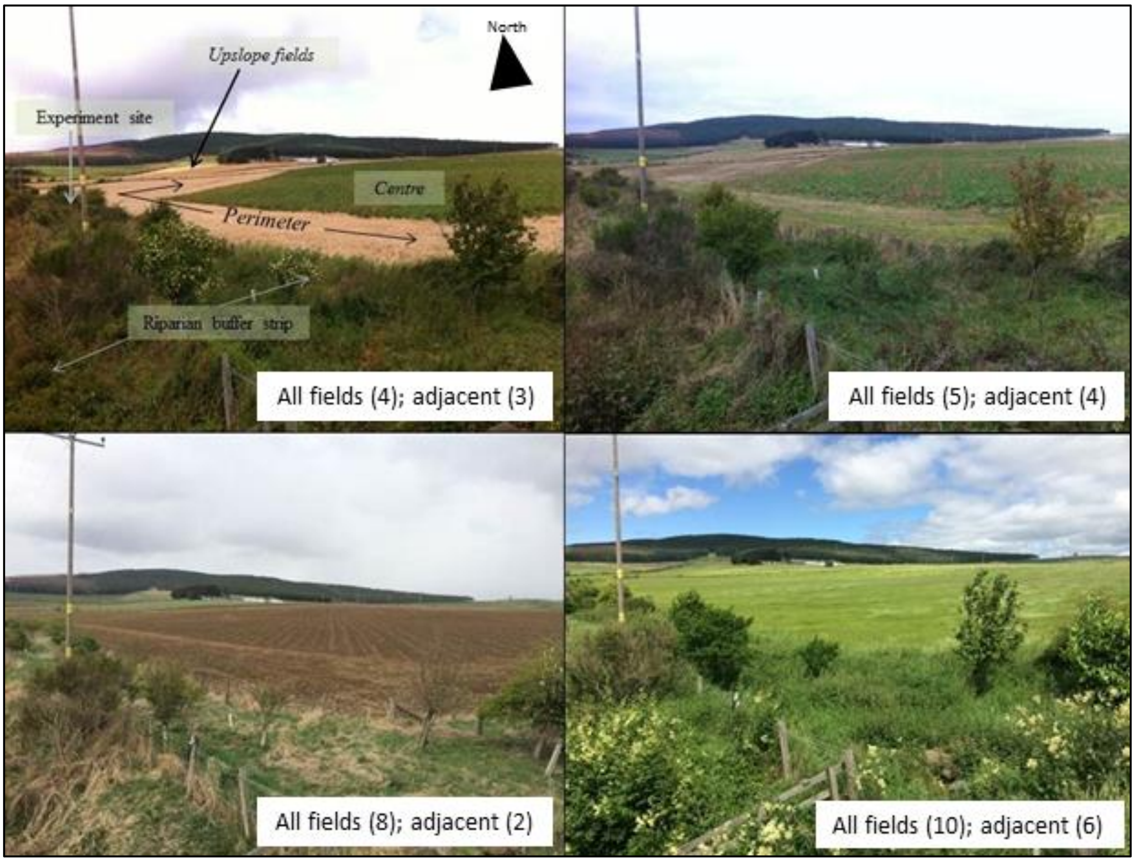



Figure 5.1. Land management of adjacent field and upslope fields. Refer to Table 1 for descriptions of categories. Top left, 21st August 2014; top right, 14th October 2014; bottom left, 27th April 2015; and bottom right, 21st July 2015.

Most events (maximum 64) occurred during land category upslope 1 (U1) and adjacent 1 (A1) when there was mostly bare soil, although these land categories existed for a longer period than the other categories (Table 5.1). Land categories U11 and A7 represent a period of no data (Table 5.1) and therefore the land management practices are unknown. However, on the last field visit (September 2015) all fields consisted of tall barley crop. This *no data* category remained part of the study as it was assumed the crops of barley would have been harvested at some point in September or early October, and thereby warranted an assessment of any runoff or infiltration events. Despite the uncertainty in the land management between September and December 2015, assessing this period of unknown land management is valuable due to the number of events that occur.

Specific land management categories are explored in more detail following the identification of runoff and infiltration events (explained in Section 5.2.7). The events indicate the land management at the time of the event and the categories that warrant further investigation and comparison.

Table 5.2. Timeline of land use management categories with corresponding precipitation totals and counts of runoff and infiltration events. Land categories highlighted in red identify those which will analysed further to understand the conditions for a runoff or infiltration event to occur.

| **From** | **19 Dec 2013** | **3 Apr 2014** | **6 May 2014** | **20 Jul 2014** | **18 Sep 2014** | **19 Dec 2014** | **30 Jan 2015** | **27 Apr 2015** | **29 May 2015** | **22 Jul 2015** | **2 Sep 2015** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **To** | **2 Apr 2014** | **5 May 2014** | **19 Jul 2014** | **17 Sep 2014** | **18 Dec 2014** | **29 Jan 2015** | **26 Apr 2015** | **28 May 2015** | **21 Jul 2015** | **1 Sep 2015** | **14 Dec 2015** |
| Upslope land category | U1 | U2 | U3 | U4 | U5 | U6 | U7 | U8 | U9 | U10 | U11 |
| Adjacent land category | A1 | A2 | A1 | A3 | A4 | A4 | A4 | A2 | A5 | A6 | A7 |
| Catchment Pcp (mm) | 338 | 56 | 150 | 201 | 291 | 40 | 75 | 77 | 153 | 108 | 203 |
| No. events | 64 | 21 | 46 | 33 | 54 | 24 | 38 | 25 | 41 | 26 | 75 |

### *5.2.2 Overland flow type*

The establishment of whether any events would likely result in either saturation excess or infiltration excess overland flow was determined by soil infiltration tests. These tests were conducted in the riparian buffer strip and its adjacent field to determine any distinction between the infiltration rate of a managed arable field and an unmanaged well-established riparian buffer strip.

The soil infiltration tests indicated the infiltration rates for the adjacent field (brown forest soil and 1.5 m tall barley crop) and buffer strip (mixed alluvial soil) are 29.5 mm/hr and 35.1 mm/hr, respectively. The lower infiltration rate in the adjacent field emphasises the difference (5.6 mm/hr) between a managed and unmanaged soil, albeit the soils differ. However, the maximum hourly intensity of catchment precipitation (15.5 mm) was less than the infiltration rates, indicating runoff is produced by saturation excess overland flow. This occurs when the soil has reached its full water storage capacity and any additional precipitation will result in runoff.

### *5.2.3 Diurnal fluctuations in surface runoff depth measurements*

Due to unforeseen technical complications with diurnal fluctuations in surface runoff depth measurements in the V-flumes, not all events could be included in the analysis. It was necessary to concentrate analysis only those events not likely to be affected. The diurnal fluctuations caused the depth being recorded in the V-flume to falsely increase from approximately sunrise, peaking at about 2pm, and then declining back to normal depth measurements in the evening (Figure 5.2). The fluctuations were more prominent in warmer months, especially summer, and strongly correlated to temperature ($R^2$ >0.7). The temperature compensation mode in the ultrasonic sensor was activated, yet the issue persisted. After several field and lab tests to rectify the issue, it was evident that the metal which encased the sensor would heat up (especially in direct sunlight or in high temperatures) and cause these false daily peaks and troughs in V-flume depths (illustrated in Figure 5.2).

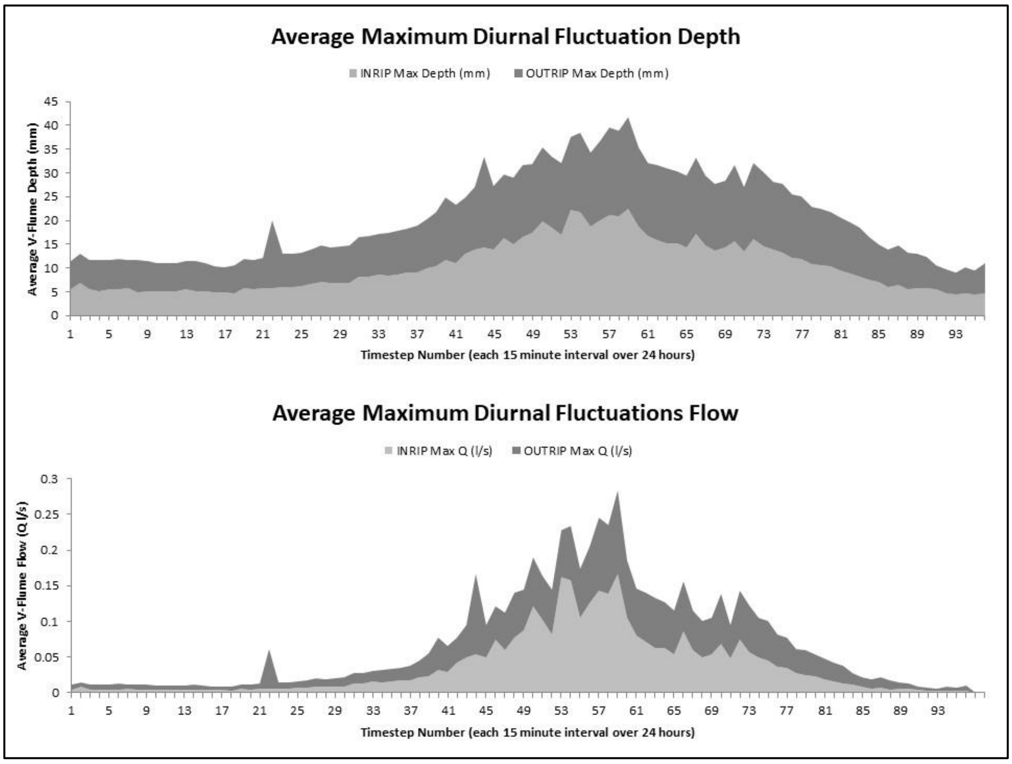



Figure 5.2. Diurnal fluctuation measurement error bands derived from the mean depth for each 15-minute timestep in one 24-hour period, over 212 days where no precipitation occurred.

To address the issue and enable analysis of the surface runoff data to be maximised, the useful data was extracted using the following steps:

- For each month, all days with no precipitation (212 days in total) over the experiment period were collated.
- For all dry days within the monthly groups, the V-flume depth data for each 15-minute interval over 24 hours (96 intervals in total) was averaged and graphed (similar to Figure 5.3).
- Only events with a depth of ≥16 mm precipitation (which was the Q5 percentile of the precipitation data for the experiment period and thereby the most extreme values for that period) and events during winter were considered for further analysis. The most extreme events and winter period would be more likely see surface runoff and diurnal influence would be limited (due to reduced direct sunlight heating the metal of the sensor).

However, as a precaution the mean diurnal values per each time step of each event were overlaid event time series graphs to ensure any surface runoff response did not correspond to diurnal fluctuations.

### *5.2.4 Event identification*

The 95th percentile events are defined as catchment precipitation totals were occurring 5% of the time (Q5 events). The Q5 events were selected to ascertain the conditions by which overland flow (surface runoff) enters the riparian buffer strip (RQ1) and compared to events where only infiltration occurred. This comparison aimed to highlight conditions that define when overland flow occurred and entered the riparian buffer strip (referred to as a runoff event). The decision framework (Chapter 3, Section 3.3.5) used to identify runoff events and infiltration events is summarised in Table 5.3. The decisions for each element of the framework are reflected and identify why events were established as being a runoff, an infiltration or rejected event.

There were twenty-three (Q5) events of which, nine were runoff events, three were infiltration events and eleven were rejected (Table 5.3). Two infiltration events were classified based on there being no surface runoff but a distinct response from soil moisture. However, infiltration event 442 is determined as such despite the INRIP V-flume showing surface runoff (Table 5.3). The contributing area of the surface runoff for event 442 is <30 $m^2$, the threshold (Section 3.3.2) which determines overland flow to be coming from out with the riparian buffer strip. As both soils respond and the contributing area is low, event 442 was established as an infiltration event. However, the other two infiltration events (events 36 and 285, Table 5.3) where no runoff was detected in the V-flume, will be examined further to ascertain whether these events are valid based on the event conditions. Assessing these conditions is necessary as a minimal response would be expected in the V-flume during a heavy precipitation event as it collects rainwater. This is based on event 172 (Table 5.3), where the runoff response is suspected to be the result of the V-flume acting a large rain gauge (due to the calculated contributing area of runoff).

All runoff events were determined by the volume of overland flow recorded in the OUTRIP V-flume and the contributing area being >2$m^2$. There were three events where the INRIP runoff also responded but only runoff event 367 shows the INRIP runoff to be connected to the hillslope as the contributing area is >30 $m^2$ (Table 5.3). Soil moisture responded during all runoff events except events 35, 200 and 201, only the OUTRIP soil moisture responded (Table 5.3).

An irregularity in the selected runoff events is the inclusion of runoff event 27 despite only partial time series data (Table 5.3). This event was observed in the field and provided field observations demonstrating overland flow entered the buffer strip (field observations are explained in Section 5.2.8). Due to the logger battery requiring replacement, only partial data was recorded. At this point in the experiment (27th January 2014), only the OUTRIP V-flume sensor was functional, meaning there was no INRIP data. There was no runoff observed in the INRIP V-flume during the site visit. A similar event not captured due to equipment failure occurred but photographs from a field visit immediately after the storm event provided insight (Section 5.2.8). This event was not included in the decision framework process as there was no monitoring data recorded due to battery failure. Rejected events were determined by:

- The lack of soil or runoff response to a Q5 event;
- Diurnal measurement error (which as expected occurs in the summer months; June, July and August);
- Logger issues; and

- The V-flume runoff volume being equivalent to acting as a rain gauge (Table 5.3).

To provide clarification and an example of a rejected event, Figure 5.3 shows event 362 where there was periodic missing data in the OUTRIP V-flume. The INRIP flow is also shown to coincide with, and be within the average of, the August diurnal fluctuations.

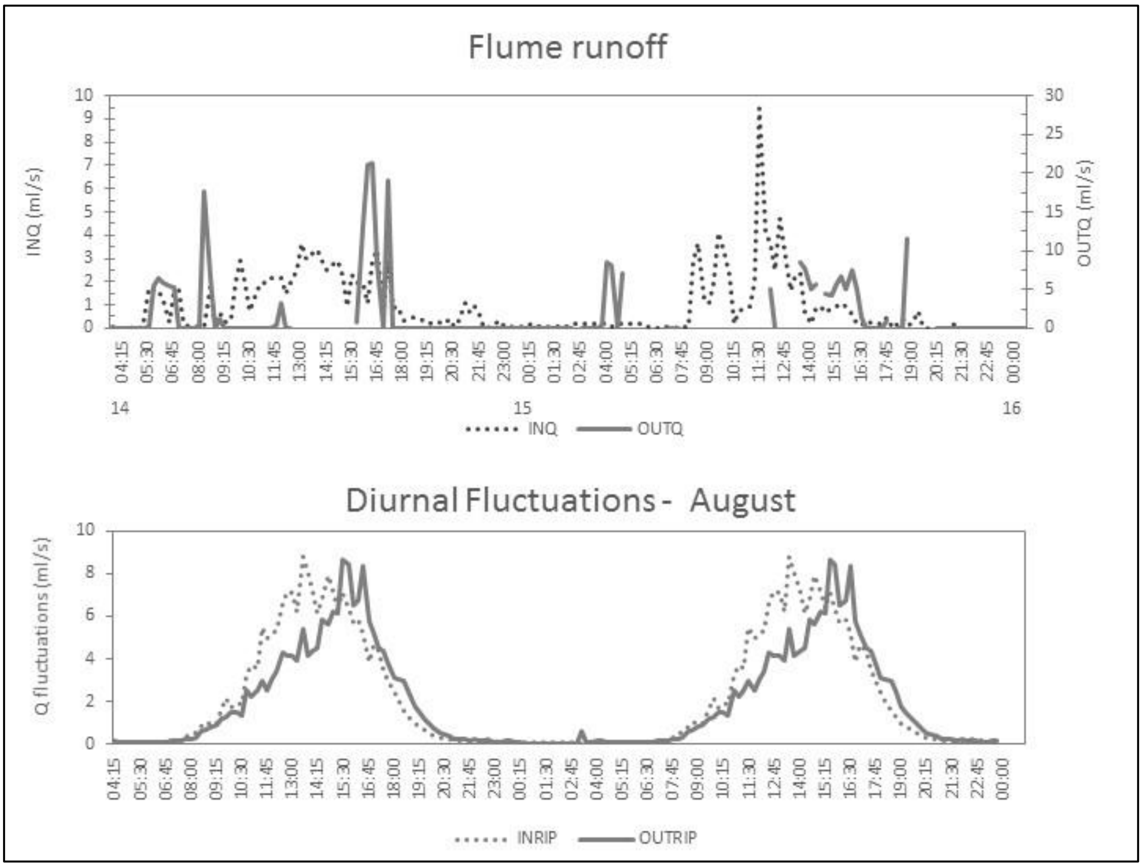



Figure 5.3. Average diurnal fluctuations for August compared to flume runoff for 14 August 2015 (event 362). Missing data is shown OUTRIP and the INRIP V-flume flow coincides with average diurnal fluctuations for August.

The example rejected event shown in Figure 5.3 demonstrates an issue encountered in the summer months. Despite a monthly maintenance regime to cut back vegetation, occasionally (nearer the end of the month period) blades of grass would intercept the tough-sonic sensor. This was addressed by cleansing the data and removing any values greater than the depth threshold of 10 cm (based on the design of the V-flume (Section 3.3.2). Ultimately, these events were not included for analysis and the event in Figure 5.4 was the only Q5 event where this was evident. Thus, the event was rejected. A further example of a rejected event is provided in Appendix 9.

### *5.2.5 Summary statistics and Mann-Whitney results for event conditions*

In order to address RQ1 and determine the conditions by which overland flow entered the riparian buffer strip, summary statistics and a Mann-Whitney statistical test was carried out on the event conditions (e.g. precipitation depth and duration). The purpose of each statistical test is outlined below:

Summary statistics (median, minimum and maximum) and boxplots: to assess the distribution of event condition variables between infiltration events and runoff events. This intends to establish whether distributions of each event condition differ for infiltration or runoff events.

- Mann-Whitney test to compare the difference between the median values of each event condition for infiltration and runoff events. This will determine if there is a statistical difference between infiltration events and runoff events for each event condition, and whether these are significant (where *P*-value is <0.05).

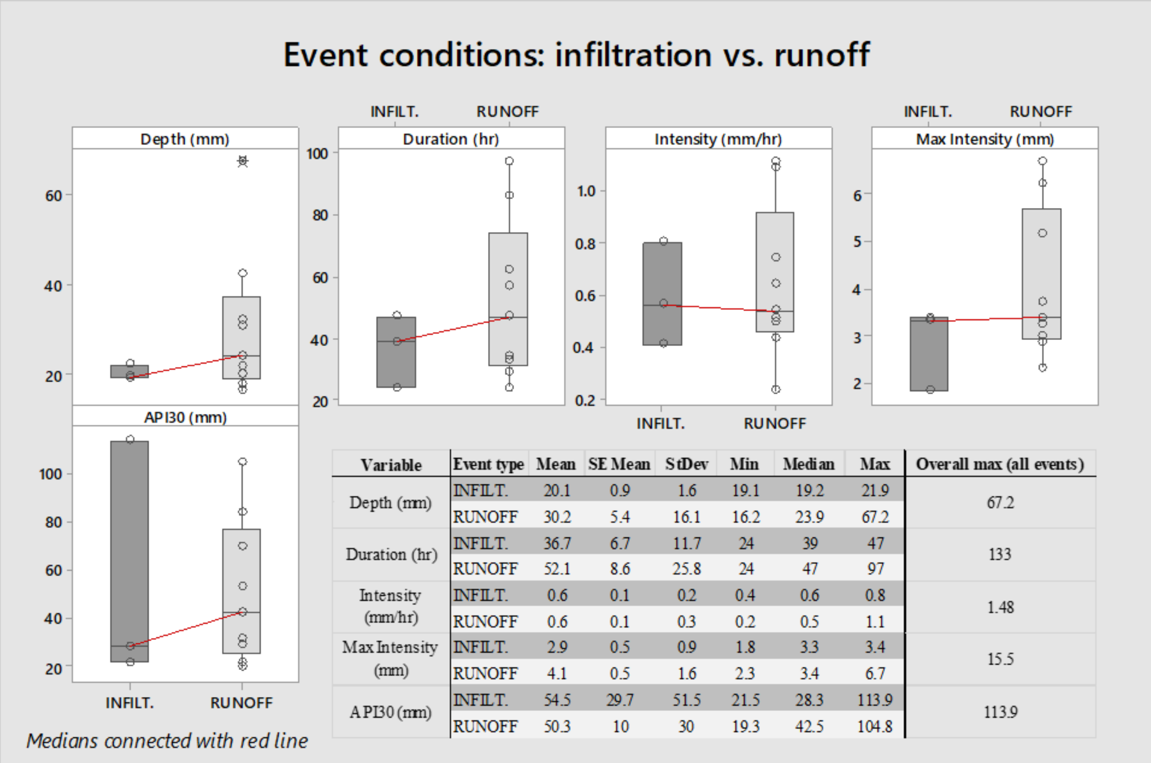
Four out of nine runoff events occurred for the four highest depth, duration and maximum (max) intensity event conditions (Figure 5.4). These event conditions demonstrate less overlap in their distributions between runoff and infiltration events. This indicates that runoff events occurred during higher values of pcp depth, duration and maximum intensity.

Reinforcing this, pcp depth and duration (but not max intensity) illustrated larger differences in their median values between infiltration events and runoff events (Figure 5.4). However, these differences in median values are shown not to be significant (*P*-value > 0.05) in the Mann-Whitney test results (Table 5.4).

There was limited distinction in the distribution of pcp intensity for infiltration and runoff events (Figure 5.4). The boxplots overlap with very low and high values being uncertain for runoff events (shown by box whiskers; Figure 5.4). There was a small difference between median pcp intensity (0.6 mm/hr for infiltration; 0.5 mm/hr for runoff) which is not statistically significant (*P*-value >0.05) (Table 5.3). Pcp intensity is therefore not likely a defining event condition of infiltration or runoff events but is explored further in Section 5.2.6.

Table 5.3. Detailed selection process for runoff and infiltration events and justification for event rejections.

| | | | | *Responses* | | | | *Land use management* | | *Contirbuting INRIP drainage area ($m^2$)* | *Contirbuting OUTRIP drainage area ($m^2$)* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Event type* | *Event* | *Date* | *Season* | *Runoff* | *Soil* | *Water table (WT)/ stream (Strm)* | *Catchment* | *Upslope* | *Adjacent* | | |
| RUNOFF EVENTS | 27 | 27-Jan-14 | Winter | Yes but partial data | Yes but partial data | No data | Aboyne and Coull discharge responds | 1 | 1 | 0 | 3600 |
| | 31 | 4-Feb-14 | Winter | Yes (OUTRIP) | Yes | No data | | 1 | 1 | 0 | 13200 |
| | 35 | 12-Feb-14 | Winter | Yes (OUTRIP), INRIP low contributing area | Yes (OUTRIP) | No data | | 1 | 1 | 9 | 22.2 |
| | 174 | 6-Oct-14 | Autumn | Yes (OUTRIP), INRIP low contributing area | Yes | WT yes, Strm no data | | 5 | 4 | 7 | 88.8 |
| | 200 | 13-Nov-14 | Autumn | Yes (OUTRIP) | Yes (OUTRIP) | WT yes, Strm no data | | 5 | 4 | 0 | 270 |
| | 201 | 15-Nov-14 | Autumn | Yes (OUTRIP), INRIP low contributing area | Yes (OUTRIP) | WT yes, Strm no data | | 5 | 4 | 1 | 73 |
| | 367 | 24-Aug-15 | Summer | Yes both respond | Yes | WT yes, Strm yes | | 10 | 6 | 148 | 113 |
| | 386 | 20-Sep-15 | Autumn | Yes (OUTRIP) | Yes | WT yes, Strm yes | | 11 | 7 | 0 | 89 |
| | 393 | 5-Oct-15 | Autumn | Yes (OUTRIP) | Yes | WT yes, Strm yes | | 11 | 7 | 0 | 78 |
| INFILTRATION EVENTS | 36 | 14-Feb-14 | Winter | Runoff did not respond | Yes (OUTRIP) | No data | | 1 | 1 | 0 | 0 |
| | 285 | 3-May-15 | Spring | Runoff did not respond | Soils respond | WT yes, Strm yes | | 8 | 2 | 0 | 0 |
| | 442 | 4-Dec-15 | Winter | INRIP contributing area $13m^2$, no OUTQ response | Soils respond | WT yes, Strm yes | | 11 | 7 | 13 | 0 |
| REJECTED EVENTS | 2 | 20-Dec-13 | Winter | Runoff did not respond | Soils do not respond | WT no response/ Strm no data | | 1 | 1 | | |
| | 4 | 27-Dec-13 | Winter | Runoff did not respond | Soils do not respond | WT no response/ Strm no data | | 1 | 1 | | |
| | 8 | 1-Jan-14 | Winter | Runoff did not respond | Soils do not respond | WT no response/ Strm no data | | 1 | 1 | | |
| | 107 | 4-Jun-14 | Summer | Yes but diurnal uncertainty | Yes | No data | | 3 | 1 | 6 | 45 |
| | 133 | 26-Jul-14 | Summer | Logger issues | Logger issues | Logger issues | | 4 | 3 | | |
| | 137 | 2-Aug-14 | Summer | Logger issues | Logger issues | Logger issues | | 4 | 3 | | |
| | 140 | 8-Aug-14 | Summer | Logger issues | Logger issues | Logger issues | | 4 | 3 | | |
| | 141 | 10-Aug-14 | Summer | Logger issues | Logger issues | Logger issues | | 4 | 3 | | |
| | 172 | 3-Oct-14 | Autumn | Minimal contributing area (rain gauge) | Soils do not respond | WT yes, Strm no | | 5 | 4 | 1 | 10 |
| | 343 | 16-Jul-15 | Summer | Yes but diurnal uncertainty | Soils respond | WT yes, Strm yes | | 9 | 5 | 3 | 25 |
| | 362 | 14-Aug-15 | Summer | Yes but missing data and diurnal uncertainty | Soils respond | WT yes, Strm yes | | 10 | 6 | 100 | 176 |




| Variable | Event type | Mean | SE Mean | StDev | Min | Median | Max | Overall max (all events) |
|---|---|---|---|---|---|---|---|---|
| Depth (mm) | INFILT. | 20.1 | 0.9 | 1.6 | 19.1 | 19.2 | 21.9 | 67.2 |
| | RUNOFF | 30.2 | 5.4 | 16.1 | 16.2 | 23.9 | 67.2 | |
| Duration (hr) | INFILT. | 36.7 | 6.7 | 11.7 | 24 | 39 | 47 | 133 |
| | RUNOFF | 52.1 | 8.6 | 25.8 | 24 | 47 | 97 | |
| Intensity (mm/hr) | INFILT. | 0.6 | 0.1 | 0.2 | 0.4 | 0.6 | 0.8 | 1.48 |
| | RUNOFF | 0.6 | 0.1 | 0.3 | 0.2 | 0.5 | 1.1 | |
| Max Intensity (mm) | INFILT. | 2.9 | 0.5 | 0.9 | 1.8 | 3.3 | 3.4 | 15.5 |
| | RUNOFF | 4.1 | 0.5 | 1.6 | 2.3 | 3.4 | 6.7 | |
| API30 (mm) | INFILT. | 54.5 | 29.7 | 51.5 | 21.5 | 28.3 | 113.9 | 113.9 |
| | RUNOFF | 50.3 | 10 | 30 | 19.3 | 42.5 | 104.8 | |

Figure 5.4. Distribution of event conditions for infiltration and runoff events, supported by summary statistics for each condition where: *SE* is standard error; *StDev* is standard deviation; and ‘INFILT’ is infiltration. The red line joins the medians of runoff and infiltration event conditions.

Table 5.4. Mann-Whitney results comparing event conditions during a runoff and infiltration event where: *CI* is the confidence interval; and ‘INFILT’ is infiltration.

| ***Variable*** | ***Event type*** | ***Median*** | ***CI for difference*** | ***Achieved confidence*** | ***P-value*** | ***Significant*** |
|---|---|---|---|---|---|---|
| Depth (mm) | INFILT.<br>RUNOFF | 19.2<br>23.9 | (-3.00129, 45.2701) | 95.8% | 0.36 | No |
| Duration (hr) | INFILT.<br>RUNOFF | 39<br>47 | (-15, 58) | 95.8% | 0.46 | No |
| Intensity (mm/hr) | INFILT.<br>RUNOFF | 0.56<br>0.54 | (-0.330183, 0.544640) | 95.8% | 1.00 | No |
| Max Intensity (mm) | INFILT.<br>RUNOFF | 3.38<br>3.32 | (-0.52, 3.35) | 95.8% | 0.46 | No |
| API30 (mm) | INFILT.<br>RUNOFF | 28.5<br>42.5 | (-85.15, 62.4) | 95.8% | 1.00 | No |

API30 displays a different result. The highest API30 (113.9 mm) was an infiltration event (Figure 5.4). However, the median for runoff events (42.5 mm) and infiltration events (28.3 mm) had a large difference in their values, which was not significant (*P-value* >0.05) (Table 5.4). Further exploration of API30 was conducted and will ascertain why the highest API30 value was an infiltration event (Section 5.2.6)

### *5.2.6 Event condition trends identified by ranking*

To understand trends in the event conditions during a runoff or an infiltration event, each variable (pcp depth, duration, intensity, maximum intensity and API30) was ranked from highest to lowest. This aimed to provide insight into trends indicating the event conditions by which overland flow entered the riparian buffer strip, as well as those which only resulted in infiltration.

During analysis of these results, it became apparent that infiltration event 36 seemed unusual. Most prominent was the ranking of API30 events (Table 5.5) where infiltration event 36 occurred during the highest API30 (113.9 mm). As mentioned in Section 5.2.4, event 36 was classified as an infiltration event due to there being no response from the INRIP or OUTRIP V-flumes (no runoff), but soil moisture responded. However, the API rankings (Table 5.5) highlight event 36 as an anomaly, especially in terms of the API30 conditions. Event 36 is suspected to be an experimental error for the following reasons:

- The event occurred during the highest API30 Table 5.5, which indicated the catchment was at its wettest within the experiment period and would suggest runoff was inevitable;
- The land management at the time was when five out of six upslope fields (U1) were bare soil and the adjacent field had a bare soil centre with short crop perimeter (A1) (Table 5.5). This would limit the degree of roughness that would otherwise slow overland flow.
- Uncertainty in the calibration equation (Section 3.3.2) and the accuracy of the ultrasonic senor measuring runoff depth in the V-flume. Their errors could result in no depths being recorded when the flume is collecting rainfall (acting as a rain gauge), which would produce a very shallow depth.

Accounting for the caution of event 36, ranking tables highlight event 36 in red and it was not considered when assessing trends. A red line on each table indicates where a visible trend stops. Each event condition is outlined in turn.

All event conditions are reflected in Table 5.6 and those highlighted in red text indicate which event conditions were likely to have resulted in runoff or infiltration. These highlighted event conditions (Table 5.6) were determined by analysing trends in the ranking tables of each event condition, which are outlined in turn.

**Antecedent conditions (API30)**

There is a clear distinction in the rankings of API30 (Table 5.5) showing runoff events dominated the top seven API30 depths (excluding event 36). This trend changes between runoff event 386 (29 mm API30) and infiltration event 442 (28 mm API30). Despite the same land categories (which is a period of no data), event 386 was in September and 442 in December. However, Table 5.6 presents an obvious difference in max intensity between these events: the runoff event (386) was 6.7 mm whereas the infiltration event was 1.8 mm.

Table 5.5. Antecedent precipitation index for preceding 30 days (API30) ranked from highest to lowest indicating runoff events (green) and infiltration events (yellow). Red text indicates a likely anomaly event, which has not been considered when ascertaining trends. The red line indicates where a trend no longer exists.

| 30 day Antecedent precipitation index (API30) | ***Rank*** | ***Event*** | ***Event type*** | ***Date*** | ***Season*** | ***Land*** | | ***API30 (mm)*** |
|---|---|---|---|---|---|---|---|---|
| | | | | | | ***Upslope*** | ***Adjacent*** | |
| | 1 | 36 | INFILT. | 14-Feb-14 | Winter | 1 | 1 | 114 |
| | 2 | 35 | RUNOFF | 12-Feb-14 | Winter | 1 | 1 | 105 |
| | 3 | 31 | RUNOFF | 4-Feb-14 | Winter | 1 | 1 | 84 |
| | 4 | 27 | RUNOFF | 27-Jan-14 | Winter | 1 | 1 | 70 |
| | 5 | 201 | RUNOFF | 15-Nov-14 | Autumn | 5 | 4 | 53 |
| | 6 | 200 | RUNOFF | 13-Nov-14 | Autumn | 5 | 4 | 43 |
| | 7 | 367 | RUNOFF | 24-Aug-15 | Summer | 10 | 6 | 31 |
| | 8 | 386 | RUNOFF | 20-Sep-15 | Autumn | 11 | 7 | 29 |
| | 9 | 442 | INFILT. | 4-Dec-15 | Winter | 11 | 7 | 28 |
| | 10 | 285 | INFILT. | 3-May-15 | Spring | 8 | 2 | 22 |
| | 11 | 174 | RUNOFF | 6-Oct-14 | Autumn | 5 | 4 | 21 |
| | 12 | 393 | RUNOFF | 5-Oct-15 | Autumn | 11 | 7 | 19 |

Two runoff events (174 and 393) rank lower than the trend breaking infiltration events (442 and 285) (Table 5.3). Despite an API30 of 21 mm (similar to infiltration event 285; 22 mm), runoff event 174 likely resulted in runoff because pcp depth was the highest for the experiment period (67.2 mm) and the max intensity was 6.2 mm (Table 5.6). The distinction is less obvious as to why event 393 resulted in runoff (Table 5.5) and is inconclusive for the following reasons:

- Precipitation depth (16.2 mm) was lower than (infiltration) events 442 (19.1 mm) and 285 (19.2 mm);
- The runoff event (393) had a duration and intensity that sits between the two infiltration events.
- All events occur in different months (May, October, and December) and season (spring, autumn, and winter).
- Albeit, the runoff event (393) had a slightly greater maximum intensity (3.7 mm) than the infiltration events (3.4 mm for event 285, and 1.8 mm for event 442).

Notwithstanding from runoff event 393, the results demonstrate overland flow entered the buffer strip when API30 ≥29 mm. However, when API30 <29 mm and pcp depth and max intensity were higher, runoff also occurred in the buffer strip, as highlighted by runoff event 174.

**Precipitation depth**

Having assessed infiltration event 36 prior to outlining the API30 rankings, it is necessary to now outline infiltration event 285 and explore the uncertainty (as indicated in Section 5.2.4) by examining results from Table 5.6. Despite the similarity in pcp depth between infiltration event 285 (19.2 mm) and infiltration event 36 (21.9 mm) (Table 5.7); and there being no response from the V-flumes, the event conditions suggest a likelihood that event 285 did result in infiltration for the following reasons:

- API30 for infiltration event 285 was similar for infiltration event 442 (22 mm and 28 mm, respectively).
- Event 285 API30 was 92 mm less than the highest API30 depth, therefore there would have been storage capacity.
- Pcp depth was also similar for infiltration events 285 and 442 (19.2 mm and 19.1 mm, respectively).
- Event 285 ranked similarly to infiltration event 442 for API30 (Table 5.5) and pcp depth (Table 5.6). With more certainty in event 442, it would be appropriate to consider event 285 as an infiltration event.

Despite no runoff presence in the V-flume (which was also the case for the experimental error event 36), event 285 remained a valid infiltration event with some uncertainty. This is justified by the lower API30 and pcp depth (which is similar to infiltration event 442), uncertainty of errors in the ultrasonic V-flume sensors and calibration equations, which could underestimate small depths of runoff in the V-flume (expected due to maximum intensity of precipitation).

Table 5.6. All event conditions for infiltration and runoff events. Red values indicate the event conditions that are likely to have resulted in either runoff or infiltration (excluding event 36 as it was an experiment error) Full table including rejected events in Appendix 10.

| | | | | *Land* | | *Precipitation* | | | | | | *INRIP runoff* | | | | *OUTRIP runoff* | | | | *INRIP soil* | | | *OUTRIP soil* | | | *Stream* | | *W. Table* | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Event* | *Event type* | *Date* | *Season* | *Upslope* | *Adjacent* | *Depth (mm)* | *Duration (hr)* | *Intensity (mm/hr)* | *Max Intensity (mm)* | *API30 (mm)* | *Average Temp. (°C)* | *Ttp (hr)* | *Qpk (ml/s)* | *Vol. (mm)* | *Contributing runoff area ($m^2$)* | *Ttp (hr)* | *Qpk (ml/s)* | *Vol. (mm)* | *Contributing runoff area ($m^2$)* | *Ttp (hr)* | *VWC Pk (%)* | *VWC change (%)* | *Ttp (hr)* | *VWC Pk (%)* | *VWC change (%)* | *Pk (m)* | *Ttp (hr)* | *Pk (mm)* | *Ttp (hr)* |
| 27 | RUNOFF | 27-Jan-14 | Winter | 1 | 1 | 20.0 | 86 | 0.2 | 3.0 | 70 | 2.3 | 31.50 | 0.0 | 0 | 0 | 31.50 | 1632.4 | 90070 | 3600 | 58.00 | 47% | 2% | 58.00 | 56% | 19% | | | | |
| 31 | RUNOFF | 4-Feb-14 | Winter | 1 | 1 | 30.7 | 57 | 0.5 | 2.9 | 84 | 3.8 | 3.50 | 0.0 | 0 | 0 | 3.25 | 2008.2 | 600542 | 13200 | 26.50 | 48% | 4% | 16.75 | 50% | 13% | | | | |
| 35 | RUNOFF | 12-Feb-14 | Winter | 1 | 1 | 17.8 | 24 | 0.7 | 3.2 | 105 | 3.1 | 7.75 | 5.4 | 226 | 9 | 7.75 | 12.8 | 585 | 22 | 9.75 | 51% | 4% | 7.50 | 42% | 13% | | | | |
| 36 | INFILT. | 14-Feb-14 | Winter | 1 | 1 | 21.9 | 39 | 0.6 | 3.3 | 114 | 2.4 | 4.75 | 0.0 | 0 | 0 | 6.75 | 0.0 | 0 | 0 | 18.50 | 51% | 1% | 19.25 | 45% | 15% | | | | |
| 174 | RUNOFF | 6-Oct-14 | Autumn | 5 | 4 | 67.2 | 62 | 1.1 | 6.2 | 21 | 8.6 | 36.00 | 3.6 | 724 | 7 | 37.25 | 163.4 | 8798 | 89 | 36.50 | 16% | 11% | 37.50 | 67% | 37% | | | 88.7 | 36.75 |
| 200 | RUNOFF | 13-Nov-14 | Autumn | 5 | 4 | 21.9 | 34 | 0.6 | 3.4 | 43 | 9.2 | 21.50 | 0.3 | 9 | 0 | 27.75 | 414.2 | 8804 | 270 | 25.50 | 28% | 28% | 26.50 | 69% | 33% | | | 74.7 | 25.00 |
| 201 | RUNOFF | 15-Nov-14 | Autumn | 5 | 4 | 42.2 | 97 | 0.4 | 2.3 | 53 | 7.7 | 83.00 | 1.5 | 72 | 1 | 34.00 | 145.5 | 4592 | 73 | 8.25 | 30% | 30% | 9.25 | 65% | 29% | | | 69.8 | 8.25 |
| 285 | INFILT. | 3-May-15 | Spring | 8 | 2 | 19.2 | 24 | 0.8 | 3.4 | 22 | 4.3 | 0.00 | 0.0 | 0 | 0 | 0.00 | 0.0 | 0 | 0 | 13.75 | 36% | 36% | 19.50 | 39% | 13% | 0.2 | 15.00 | 96.8 | 14.00 |
| 367 | RUNOFF | 24-Aug-15 | Summer | 10 | 6 | 32.1 | 29 | 1.1 | 6.7 | 31 | 13.9 | 16.00 | 40.2 | 6616 | 148 | 19.25 | 44.1 | 5487 | 113 | 4.00 | 45% | 7% | 19.50 | 45% | 9% | 0.3 | 19.25 | 87.0 | 4.00 |
| 386 | RUNOFF | 20-Sep-15 | Autumn | 11 | 7 | 23.9 | 47 | 0.5 | 5.2 | 29 | 11.0 | 12.50 | 0.0 | 0 | 0 | 19.00 | 28.7 | 3172 | 89 | 19.25 | 41% | 9% | 22.75 | 40% | 39% | 0.2 | 22.50 | 42.5 | 22.75 |
| 393 | RUNOFF | 5-Oct-15 | Autumn | 11 | 7 | 16.2 | 33 | 0.5 | 3.7 | 19 | 13.2 | 24.50 | 0.0 | 0 | 0 | 19.25 | 19.6 | 1881 | 78 | 20.00 | 40% | 10% | 20.25 | 39% | 13% | 0.2 | 19.50 | 39.5 | 20.25 |
| 442 | INFILT. | 4-Dec-15 | Winter | 11 | 7 | 19.1 | 47 | 0.4 | 1.8 | 28 | 7.5 | 31.00 | 2.6 | 366 | 13 | 31.75 | 0.2 | 3 | 0 | 31.50 | 44% | 5% | 32.25 | 70% | 32% | 0.3 | 32.25 | 77.5 | 33.00 |

Table 5.7. Precipitation depth ranked from highest to lowest indicating runoff events (green) and infiltration events (yellow). Red text indicates a likely anomaly event, which has not been considered when ascertaining trends. The red line indicates where a trend no longer exists.

| Precipitation depth | Rank | Event | Event type | Date | Season | Land: Upslope | Land: Adjacent | Depth (mm) |
|---|---|---|---|---|---|---|---|---|
| | 1 | 174 | RUNOFF | 6-Oct-14 | Autumn | 5 | 4 | 67.2 |
| | 2 | 201 | RUNOFF | 15-Nov-14 | Autumn | 5 | 4 | 42.2 |
| | 3 | 367 | RUNOFF | 24-Aug-15 | Summer | 10 | 6 | 32.1 |
| | 4 | 31 | RUNOFF | 4-Feb-14 | Winter | 1 | 1 | 30.7 |
| | 5 | 386 | RUNOFF | 20-Sep-15 | Autumn | 11 | 7 | 23.9 |
| | 6 | 36 | INFILT. | 14-Feb-14 | Winter | 1 | 1 | 21.9 |
| | 7 | 200 | RUNOFF | 13-Nov-14 | Autumn | 5 | 4 | 21.9 |
| | 8 | 27 | RUNOFF | 27-Jan-14 | Winter | 1 | 1 | 20.0 |
| | 9 | 285 | INFILT. | 3-May-15 | Spring | 8 | 2 | 19.2 |
| | 10 | 442 | INFILT. | 4-Dec-15 | Winter | 11 | 7 | 19.1 |
| | 11 | 35 | RUNOFF | 12-Feb-14 | Winter | 1 | 1 | 17.8 |
| | 12 | 393 | RUNOFF | 5-Oct-15 | Autumn | 11 | 7 | 16.2 |

Precipitation depth ranking illustrated the highest eight pcp depths resulted runoff entering the buffer strip, all of which were ≥20 mm (Table 5.7). The ninth and tenth rank of events nevertheless were infiltration events with similar pcp depths (event 285 = 19.2 mm; event 442 = 19.1 mm), which occurred in winter, but with different land management categories (event 285 = U8 and A2, event 442 = U11 and A7) (Table 5.7). Despite the land categories for event 442 being when there is no data, it is likely the spring barley was harvested by this time (4$^{th}$ December) having been sown in late May (Table 5.2) and the fields would either have been bare soil (A2) or short crop (A5). However, this is an assumption. Despite runoff events having occurred when pcp depth ≥20 mm, this does not explain why two other runoff events ranked lower than the infiltration events (Table 5.7). Inspecting all event conditions in Table 5.6 indicates:

- Runoff event 35 API30 differed from infiltration events 285 and 442 (105 mm, 22 mm, and 28 mm, respectively). API30 was the differentiating variable of runoff and infiltration occurring in these events.
- Runoff event 393 max intensity differed from infiltration events 285 and 442 (3.7 mm, 3.4 mm, and 1.8 mm, respectively). Max intensity was the differentiating event condition.
- Runoff event 27 API30 differed from infiltration events 285 and 442 (70 mm, 22 mm, and 28 mm, in turn). They also differed in terms of event duration (86 hr, 24 hr, and 47 hr, respectively).

Overall, the ranking threshold for pcp depth indicated runoff entered the riparian buffer strip when pcp depth ≥20 mm. Precipitation depths <20 mm resulted in infiltration with exception to when API30 was high (the catchment was wetter), and/or max intensity was high.

**Event duration**

Duration ranking had a less defined threshold with the highest five being runoff events and two infiltration events being spread between in rank six and eleven (Table 5.8). Runoff event 386 and infiltration event 442 are comparative with a duration of 47 hr, the same land category (with uncertainty as this was the no data period) and similar API30 (Table 5.8). Nonetheless, the key differentiation indicating why runoff entered the buffer strip was the difference in maximum intensity and season (event 386 = 5.2 mm in autumn; event 442= 1.8 mm in winter, Table 5.6). Maximum intensity was once more the differentiating factor between infiltration event 442 and the lower ranked runoff events 200, 367, and 393 (1.8 mm, 3.4 mm, 6.7 mm and 3.7 mm, respectively) (Table 5.6).

This trend continues when comparing runoff event 367 and infiltration event 285 in which both had 24hr event duration, but maximum intensity differed (6.7 mm and 3.4 mm, in turn). On the other hand, these two events also demonstrated differences in their pcp depth and pcp intensity: the runoff event (367) had higher values (Table 5.6). Land categories and season also differed making it challenging to distinguish why these two events had two different outcomes (runoff and infiltration). Overall, for event durations ≥47hr runoff entered the buffer strip. Yet infiltration was observed to occur for durations ≤47hr, unless API30 was high or max intensity was high, resulting in runoff entering the buffer strip.

Table 5.8. Event duration ranked from highest to lowest indicating runoff events (green) and infiltration events (yellow). Red text indicates a likely anomaly event, which has not been considered when ascertaining trends. The red line indicates where a trend no longer exists.

| | *Rank* | *Event* | *Event type* | *Date* | *Season* | *Land* | | *Duration (hr)* |
|---|---|---|---|---|---|---|---|---|
| | | | | | | *Upslope* | *Adjacent* | |
| **Duration** | 1 | 201 | RUNOFF | 15-Nov-14 | Autumn | 5 | 4 | 97 |
| | 2 | 27 | RUNOFF | 27-Jan-14 | Winter | 1 | 1 | 86 |
| | 3 | 174 | RUNOFF | 6-Oct-14 | Autumn | 5 | 4 | 62 |
| | 4 | 31 | RUNOFF | 4-Feb-14 | Winter | 1 | 1 | 57 |
| | 5 | 386 | RUNOFF | 20-Sep-15 | Autumn | 11 | 7 | 47 |
| | 6 | 442 | INFILT. | 4-Dec-15 | Winter | 11 | 7 | 47 |
| | 7 | 36 | INFILT. | 14-Feb-14 | Winter | 1 | 1 | 39 |
| | 8 | 200 | RUNOFF | 13-Nov-14 | Autumn | 5 | 4 | 34 |
| | 9 | 393 | RUNOFF | 5-Oct-15 | Autumn | 11 | 7 | 33 |
| | 10 | 367 | RUNOFF | 24-Aug-15 | Summer | 10 | 6 | 29 |
| | 11 | 285 | INFILT. | 3-May-15 | Spring | 8 | 2 | 24 |
| | 12 | 35 | RUNOFF | 12-Feb-14 | Winter | 1 | 1 | 24 |

**Precipitation intensity**

The clarity of any trend in the ranking of precipitation intensities was more ambiguous and required assessment of event conditions for the top five ranked events (Table 5.9). Comparing the top five ranked events (Table 5.6) distinguished conditions that resulted in event 285 (ranked third) being an infiltration event and clarified why it ranked highly for precipitation intensity, land management categories notwithstanding:

- The low API30 for event 285 (22 mm) combined with lower maximum intensity (3.4 mm) distinguishes why event 285 resulted in infiltration only:
    - Runoff events 367 and 174 had similar API30 (31 mm and 21 mm, respectively) but higher maximum intensities (6.7 mm and 6.2 mm, in turn).
    - Runoff event 367 also had a very high pcp depth (67.2 mm).
    - Runoff event 35 had similar pcp depth (17.8 mm), duration (24 hr) and maximum intensity (3.2 mm) to infiltration event 285 (19.2 mm, 24 hr and 3.4 mm, respectively). However, runoff event 35 had almost five times the depth of API30 (105 mm) compared to infiltration event 285 (22 mm).
    - Runoff event 200 had similar pcp depth (21.9 mm) and maximum intensity (3.4 mm) to infiltration event 285. However, runoff event 200 event duration (34 hr) and API30 (43 mm) differed to infiltration event 285.

At the lower ranks of pcp intensity (Table 5.9), infiltration event 442 occurred (rank eleven). Comparable to the assessment of infiltration event 285, the distinction between a runoff and infiltration event was the maximum intensity and antecedent conditions (API30). Contrasting runoff events 201 (rank ten) and 27 (rank twelve) to infiltration event 442 (rank eleven) highlighted the following (land categories notwithstanding):

- The low API30 for infiltration event 442 (28 mm) combined with lower maximum intensity (1.8 mm) distinguishes why event 442 resulted in infiltration only:
    - Runoff event 201 had higher pcp depth (42.2 mm), maximum intensity (3 mm) and API30 (53 mm) than infiltration 442 (19.1 mm, 1.8 mm and 28 mm, respectively).
    - Runoff event 27 had similar pcp depth (20 mm), higher duration (86 hr), higher maximum intensity (3 mm) and higher API30 (70 mm) than infiltration event 285.

The assessment of pcp intensity ranks highlights the function of API30 and maximum intensity in determining whether runoff occurred. There is an interaction between these event conditions whereby API30 can be low (≤21 mm) and result in a runoff event in the buffer strip when maximum intensity and pcp depth is higher (≥3.7 mm and ≥23.9 mm, respectively), as illustrated by Table 5.6.

Table 5.9. Precipitation intensity ranked from highest to lowest indicating runoff events (green) and infiltration events (yellow). Red text indicates a likely anomaly event, which has not been considered when ascertaining trends.

| Intensity | | | | | | Land | | |
|---|---|---|---|---|---|---|---|---|
| | *Rank* | *Event* | *Event type* | *Date* | *Season* | *Upslope* | *Adjacent* | *Intensity (mm/hr)* |
| | 1 | 367 | RUNOFF | 24-Aug-15 | Summer | 10 | 6 | 1.1 |
| | 2 | 174 | RUNOFF | 6-Oct-14 | Autumn | 5 | 4 | 1.1 |
| | 3 | 285 | INFILT. | 3-May-15 | Spring | 8 | 2 | 0.8 |
| | 4 | 35 | RUNOFF | 12-Feb-14 | Winter | 1 | 1 | 0.7 |
| | 5 | 200 | RUNOFF | 13-Nov-14 | Autumn | 5 | 4 | 0.6 |
| | 6 | 36 | INFILT. | 14-Feb-14 | Winter | 1 | 1 | 0.6 |
| | 7 | 31 | RUNOFF | 4-Feb-14 | Winter | 1 | 1 | 0.5 |
| | 8 | 386 | RUNOFF | 20-Sep-15 | Autumn | 11 | 7 | 0.5 |
| | 9 | 393 | RUNOFF | 5-Oct-15 | Autumn | 11 | 7 | 0.5 |
| | 10 | 201 | RUNOFF | 15-Nov-14 | Autumn | 5 | 4 | 0.4 |
| | 11 | 442 | INFILT. | 4-Dec-15 | Winter | 11 | 7 | 0.4 |
| | 12 | 27 | RUNOFF | 27-Jan-14 | Winter | 1 | 1 | 0.2 |

**Maximum hourly precipitation intensity**

It has been indicated max intensity was an influencing factor on runoff events occurring in the buffer strip. The ranks of max intensity (Table 5.10) determine infiltration event 285 to rank fifth. As highlighted previously, this was due to a low API30 (22 mm). There was little to determine why event 393 resulted in runoff entering the buffer strip other than max intensity (3.7 mm) was slightly higher than infiltration event 285 (3.4 mm). Runoff event 393 had a lower pcp depth (16.2 mm) over a longer period (33 hr) and a lower API30 (19 mm) compared to infiltration event 285 (19.2 mm, 24 hr and 22 mm, respectively) (Table 5.6). Nonetheless, runoff event 393 occurred in October and infiltration event 285 in May, and both had differing adjacent land categories (Table 5.6). Notwithstanding, the max intensity trend is clear: overland flow entered the buffer strip when max intensity >1.8 mm (Table 5.10). An exception was demonstrated by infiltration event 285 when API30 was low (22 mm).

Table 5.10. Maximum hourly precipitation intensity ranked from highest to lowest indicating runoff events (green) and infiltration events (yellow). Red text indicates a likely anomaly event, which has not been considered when ascertaining trends. The red line indicates where a trend no longer exists.

| | *Rank* | *Event* | *Event type* | *Date* | *Season* | *Upslope* | *Adjacent* | *Max intensity (mm)* |
|---|---|---|---|---|---|---|---|---|
| **Max Intensity** | 1 | 367 | RUNOFF | 24-Aug-15 | Summer | 10 | 6 | 6.7 |
| | 2 | 174 | RUNOFF | 6-Oct-14 | Autumn | 5 | 4 | 6.2 |
| | 3 | 386 | RUNOFF | 20-Sep-15 | Autumn | 11 | 7 | 5.2 |
| | 4 | 393 | RUNOFF | 5-Oct-15 | Autumn | 11 | 7 | 3.7 |
| | 5 | 285 | INFILT. | 3-May-15 | Spring | 8 | 2 | 3.4 |
| | 6 | 200 | RUNOFF | 13-Nov-14 | Autumn | 5 | 4 | 3.4 |
| | 7 | 36 | INFILT. | 14-Feb-14 | Winter | 1 | 1 | 3.3 |
| | 8 | 35 | RUNOFF | 12-Feb-14 | Winter | 1 | 1 | 3.2 |
| | 9 | 27 | RUNOFF | 27-Jan-14 | Winter | 1 | 1 | 3.0 |
| | 10 | 31 | RUNOFF | 4-Feb-14 | Winter | 1 | 1 | 2.9 |
| | 11 | 201 | RUNOFF | 15-Nov-14 | Autumn | 5 | 4 | 2.3 |
| | 12 | 442 | INFILT. | 4-Dec-15 | Winter | 11 | 7 | 1.8 |

**Event conditions for events with the highest contributing runoff area**

Understanding conditions when the overland flow entering the buffer strip was connected to the hillslope is useful to indicate when the riparian buffer strip was most effective at attenuating runoff. The event conditions that existed during runoff events with the highest contributing runoff area ($m^2$) for OUTRIP and INRIP are highlighted (in red) in Table 5.11. There were no distinctions in specific event conditions that resulted in greater contributing runoff area OUTRIP and INRIP. The two highest contributing runoff area for OUTRIP (event 27 and 31) coincide with high API30 (84 mm and 70 mm, respectively) and max intensity (2.9 mm and 3.0 mm, in turn). Pcp depth is also relatively high (30.7 mm and 20.0 mm, respectively). Yet, other events (e.g. 174 and 367) had greater max intensity, pcp intensity, and pcp depth for which, OUTRIP contributing runoff area was relatively small (89 $m^2$ and 113 $m^2$, correspondingly) in comparison to the highest two runoff areas (13’200 $m^2$ and 3’600 $m^2$). API30 however, was low for event 174 (21 mm) and event 367 (31 mm). Land categories for event 174 (A4; short crop perimeter, swede growth centre) and event 367 (A6; tall crop) were different from event 27 (A1; short crop perimeter, bare soil centre) and event 31 (A1). Event 367 was the only event when the contributing runoff area INRIP was connected to the hillslope.

Table 5.11. Event conditions during the highest contributing runoff area ($m^2$) during runoff events (highlighted in red)

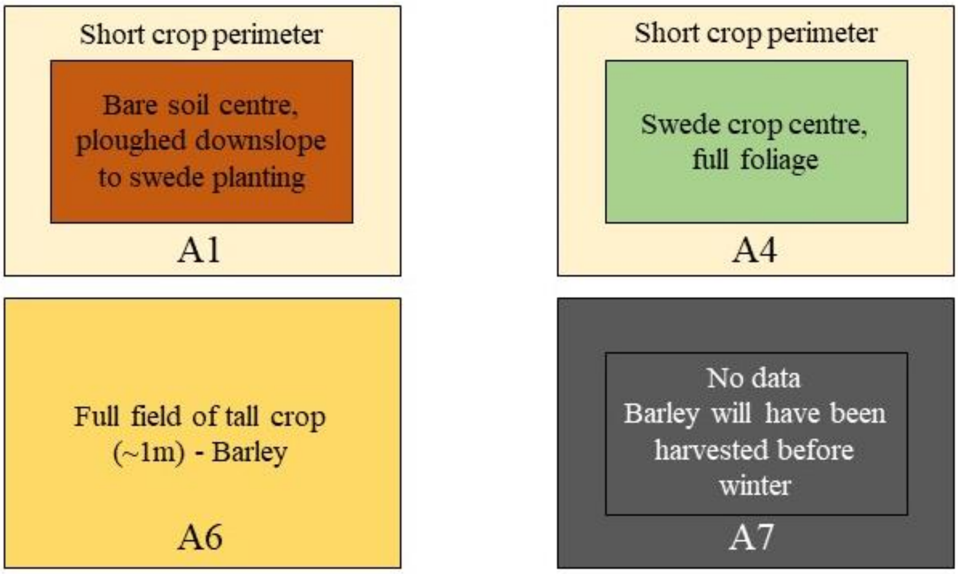
| | | | Land | | Precipitation | | | | | OUTRIP runoff | | | | INRIP runoff | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Runoff event*** | ***Date*** | ***Season*** | ***Upslope*** | ***Adjacent*** | ***Depth (mm)*** | ***Duration (hr)*** | ***Intensity (mm/hr)*** | ***Max Intensity (mm)*** | ***API30 (mm)*** | ***Ttp (hr)*** | ***Qpk (ml/s)*** | ***Vol. (mm)*** | ***Contributing runoff area ($m^2$)*** | ***Ttp (hr)*** | ***Qpk (ml/s)*** | ***Vol. (mm)*** | ***Contributing runoff area ($m^2$)*** |
| 27 | 27-Jan-14 | Winter | 1 | 1 | 20.0 | 86 | 0.2 | 3.0 | 70 | 31.50 | 1632.4 | 90070 | 3600 | 31.50 | 0.0 | 0 | 0 |
| 31 | 4-Feb-14 | Winter | 1 | 1 | 30.7 | 57 | 0.5 | 2.9 | 84 | 3.25 | 2008.2 | 600542 | 13200 | 3.50 | 0.0 | 0 | 0 |
| 35 | 12-Feb-14 | Winter | 1 | 1 | 17.8 | 24 | 0.7 | 3.2 | 105 | 7.75 | 12.8 | 585 | 22 | 7.75 | 5.4 | 226 | 9 |
| 174 | 6-Oct-14 | Autumn | 5 | 4 | 67.2 | 62 | 1.1 | 6.2 | 21 | 37.25 | 163.4 | 8798 | 89 | 36.00 | 3.6 | 724 | 7 |
| 200 | 13-Nov-14 | Autumn | 5 | 4 | 21.9 | 34 | 0.6 | 3.4 | 43 | 27.75 | 414.2 | 8804 | 270 | 21.50 | 0.3 | 9 | 0 |
| 201 | 15-Nov-14 | Autumn | 5 | 4 | 42.2 | 97 | 0.4 | 2.3 | 53 | 34.00 | 145.5 | 4592 | 73 | 83.00 | 1.5 | 72 | 1 |
| 367 | 24-Aug-15 | Summer | 10 | 6 | 32.1 | 29 | 1.1 | 6.7 | 31 | 19.25 | 44.1 | 5487 | 113 | 16.00 | 40.2 | 6616 | 148 |
| 386 | 20-Sep-15 | Autumn | 11 | 7 | 23.9 | 47 | 0.5 | 5.2 | 29 | 19.00 | 28.7 | 3172 | 89 | 12.50 | 0.0 | 0 | 0 |
| 393 | 5-Oct-15 | Autumn | 11 | 7 | 16.2 | 33 | 0.5 | 3.7 | 19 | 19.25 | 19.6 | 1881 | 78 | 24.50 | 0.0 | 0 | 0 |

### *5.2.7 Influence of land management and seasonal event conditions on runoff events*

The following results aim to ascertain whether land management of the riparian buffer strip's adjacent field influenced the OUTRIP runoff Ttp, Qpk, runoff volume, or contributing runoff area during runoff events in the buffer strip. Seasonal event conditions were also considered alongside land management to understand the conditions when overland flow entering the riparian buffer strip was exacerbated or reduced.

To enable comparison between land categories, Figure 5.5 provides a simplified schematic of the adjacent field and the land management employed for each of the four land categories when a runoff event occurred. Category A7 where no data was available, remains included in this analysis as one event occurred in autumn and the other in winter, by which time it is assumed the full field of barley crop would have been harvested.

Three runoff events occurred during land categories A1 and A4 in winter and autumn, respectively (Figure 5.5). These two land categories were compared and analysed, followed by observations of the remaining land categories using Figure 5.5 and Figure 5.6.




| *Adjacent land category* | *Category description* | *No. runoff events* | *Season* | *Runoff event no.* | *Min temp* | *Max temp* | *Mean temp* |
|---|---|---|---|---|---|---|---|
| A1 | Short crop perimeter, bare soil centre | 3 | Winter | 27 | 0.4 | 5.2 | 2.3 |
| | | | | 31 | -1.5 | 6.8 | 3.8 |
| | | | | 35 | 0.5 | 5.1 | 3.1 |
| A4 | Short crop perimeter, swede growth centre | 3 | Autumn | 174 | 4.2 | 14.5 | 8.6 |
| | | | | 200 | 2.8 | 11.3 | 9.2 |
| | | | | 201 | 2.6 | 9.5 | 7.7 |
| A6 | All tall crop (barley) | 1 | Summer | 367 | 11.7 | 16.9 | 13.9 |
| A7 | No data. But Barley would be harvested before Winter | 2 | Autumn | 386 | 9.1 | 15.1 | 11.0 |
| | | | Winter | 393 | 11.3 | 14.6 | 13.2 |

Figure 5.5. Adjacent land categories for runoff events.

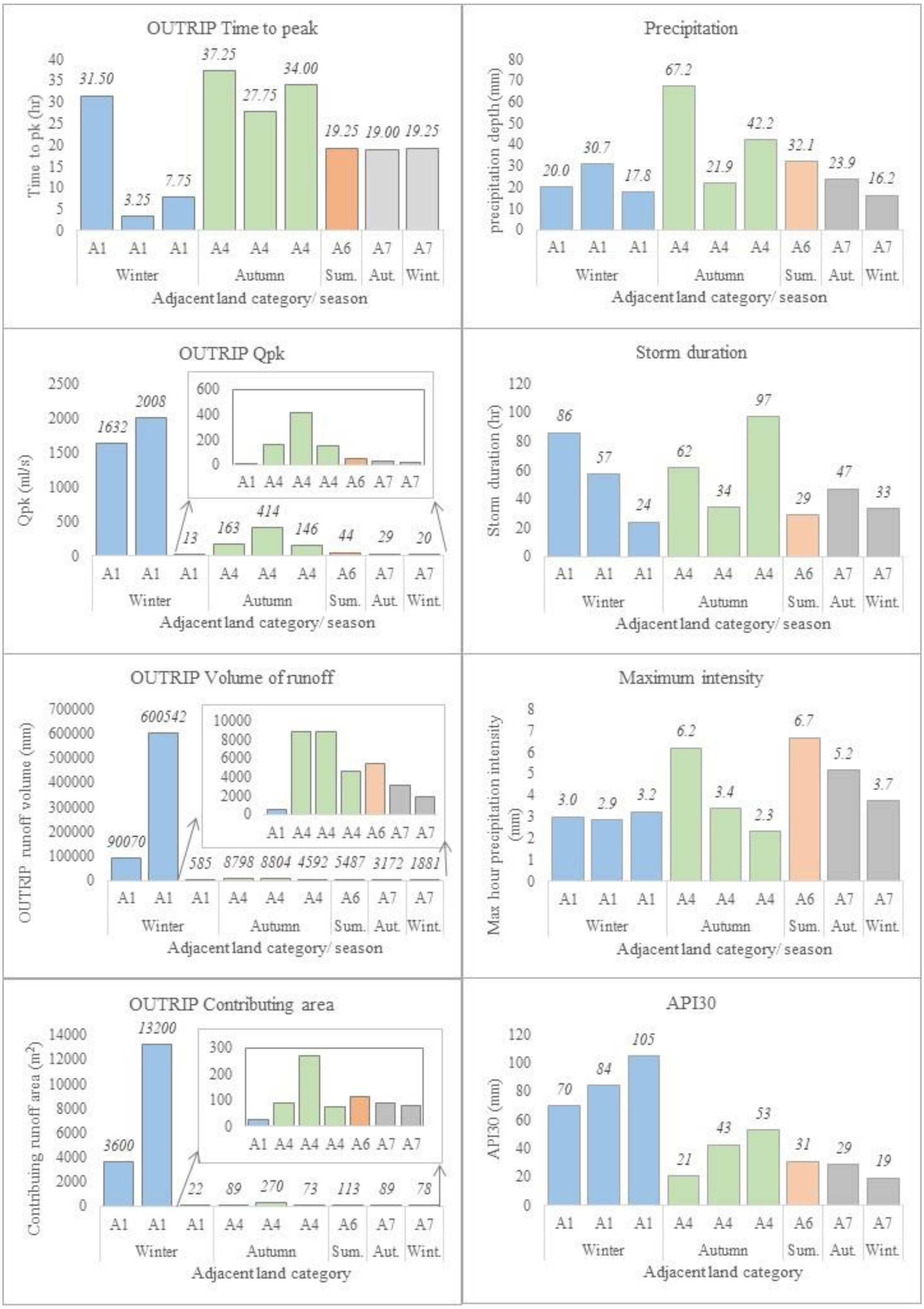



Figure 5.6. Comparison of runoff response during adjacent land categories, season and event conditions. Blue columns represent land category A1; green columns represent land category A4; amber columns represent land category A6; and grey columns represent land category A7.

In land category A1 (Figure 5.5 and Figure 5.6), two of the highest OUTRIP Qpk, volume of runoff and contributing area occurred. Yet the third A1 event (event 35, Figure 5.5) had the lowest values for all runoff events. The low values of the runoff response variables coincided with the highest API30 (105 mm) and had a similar value of max intensity compared to the other A1 land categories (3.0 mm, 2.9 mm, and 3.2 mm, chronologically). Yet, the response from this event (35) was minimal compared to all other runoff events. Event 27 was observed on a field visit to be a rainfall event, but due to the daily temperature range (Figure 5.5), there is a possibility that event 35 was a snowfall event, hence the absence of the large runoff response similar to that of event 27 and 31.


Figure 5.7. Photographs illustrating the difference between adjacent land category A1 and A4.

Contrasting land category A1 and A4 (Figure 5.5), there are several key differences indicating why land category A1 (with exception to the lowest runoff responses for event 35) had the highest values for OUTRIP Qpk, OUTRIP volume of runoff, and OUTRIP contributing runoff area:

- Season and event conditions:
    - The three events for land category A1 occurred in winter whereas the three events for land category A4 occurred in autumn (Figure 5.6). The maximum temperature ranges were between 5.1-6.8°C for the A1 winter events, and between 9.5-14.5°C for the A4 autumn events (Figure 5.5).
    - Two of the three highest precipitation depths for A4 events in autumn were higher than the three winter events of A1 land category, but the highest three API30 depths occurred during the A1 winter events (Figure 5.6).
    - With exception to the A4 event when maximum intensity was 6.2 mm, the values for this event condition were similar across A1 and A4 runoff events (Figure 5.6).
    - Wetter antecedent conditions in winter (A1 events), higher pcp depths in autumn (A4 events), similar maximum intensity and fluctuating event durations for winter and autumn.
- Land management conditions:
    - The centre of the adjacent field had bare soil in the centre (as illustrated in Figure 5.6 and picture A1 of Figure 5.7). The area of ploughed bare soil sits

over the steepest part of the sloping adjacent field. This same area of land had swede growing for land category A4 (Figure 5.5 and Figure 5.7).

- Less vegetation and bare soil ploughed in a downslope direction would limit roughness, interception and any storage provided within vegetation.

The comparative results above indicate it is difficult to differentiate whether land management or seasonal event conditions influence the magnitude of OUTRIP Qpk, OUTRIP volume of runoff and OUTRIP contributing area. But the coincidence of land management conditions (A1, bare soil on sloping agricultural land), which are known to exacerbate runoff (see Chapter 2, Section 2.3), being implemented during the highest OUTRIP Qpk, volume of runoff and contributing area suggests that seasonal event conditions and land management have a simultaneous impact on the magnitude of overland flow entering the riparian buffer strip. For example:

- Land category A1 in winter did not have high precipitation depths, but API30 was higher in winter, causing any precipitation event to have less capacity for storage in the catchment, and producing overland flow.
- More bare soil on the hillslope in winter (A1 events) would limit interception of precipitation, roughness, evaporation (which is low in winter) and water storage within vegetation itself.
- Land category A4 however, had higher autumnal precipitation depths but lower API30 depths, providing greater capacity for catchment storage of precipitation events.
- A greater abundance of crop on the hillslope in autumn (A4 events) would enhance the available storage capacity provided by lower API30; with greater evaporation in warmer daily temperatures; and more vegetation to provide roughness, interception and storage.

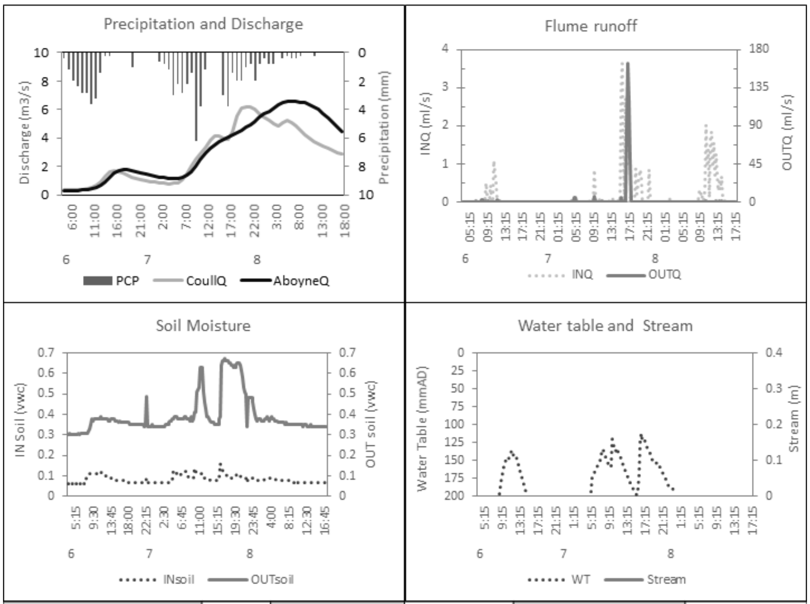
In contrast, the runoff event that occurred in summer during land category A6 (Figure 5.8) was when the adjacent field had ~1 m high barley crop across the entire field. The runoff response for this event (367) is compared to runoff event 174 during land category A4 where it shared a similar API30 (21 mm and 31 mm, respectively) and both had similar high max intensities (6.7 mm and 6.2 mm, respectively). These two land categories (A4 and A6) had crops in the adjacent field, albeit category A4 had a short crop perimeter. When comparing the time series of each event (event 174 in Figure 5.9 and event 367 in Figure 5.10), both endured a double peak in precipitation and a catchment response is evident from the discharge at Coull and Aboyne. The main differences between these runoff events are highlighted in Table 5.12. Despite more vegetation cover during the summer runoff event (367) and land category A6, the shorter duration of high intensity precipitation nevertheless resulted in overland flow entering the riparian buffer strip.

Table 5.12. Comparison of key differences in event conditions during events 174 (adjacent land category A4) and event 367 (adjacent land category A6).

| | ***A4 (event 174)*** | ***A6 (event 367)*** |
|---|---|---|
| Precipitation depth | 67.2 mm | 32.1 mm |
| Average precipitation intensity | 1.02 mm | 1.11 mm |
| Maximum intensity | 6.2 mm | 6.7 mm |
| Duration | 62 hr | 29 hr |

Figure 5.8. Adjacent land category A6 where the full field was a tall barley crop (August 2015).

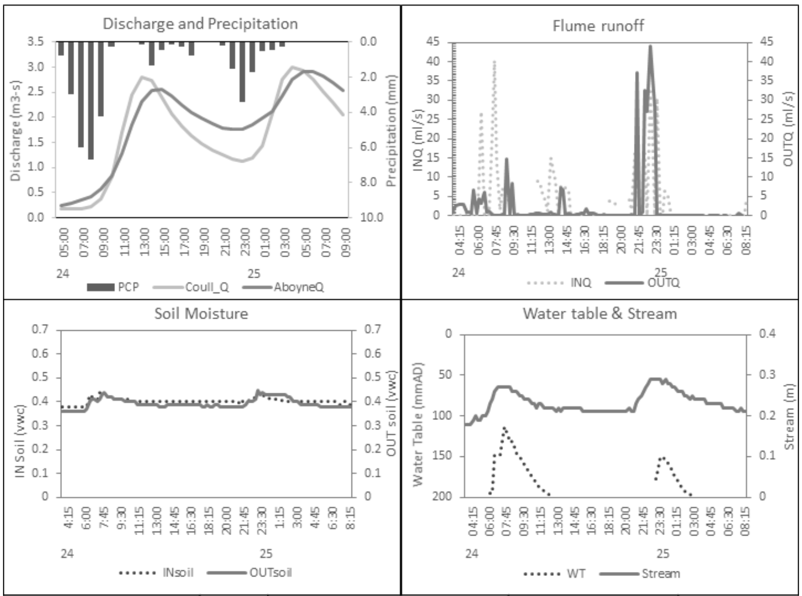
**EVENT 174– Start 6 October 2014 – Runoff event**




| | | | | | |
|---|---|---|---|---|---|
| **Depth (mm)** | 67.2 | **INQ Area (m²)** | 7 | **INRIP Q Ttp (hr)** | 36 |
| **Duration (hr)** | 62 | **OUTQ Area (m²)** | 88.8 | **OUTRIP Q Ttp (hr)** | 37.5 |
| **Avg Intensity (mm/hr)** | 1.02 | **Coull Ttp (hr)** | 42 | **INRIP soil Ttp (hr)** | 36.5 |
| **Max Intensity (mm/hr)** | 6.2 | **Aboyne Ttp (hr)** | 52 | **OUTRIP soil Ttp (hr)** | 37.5 |
| **API30 (mm)** | 21 | **Land Use** | Upslope (U5): all short crop<br>Adjacent (A6): all tall crop | | |

Figure 5.9. Time series, event conditions and runoff conditions for event 174.

**EVENT 367 – Start 24 Aug 2015 – Runoff event**




| | | | | | |
|---|---|---|---|---|---|
| **Depth (mm)** | 32.1 | **INQ Area (m²)** | 148 | **INRIP Q Ttp (hr)** | 16 |
| **Duration (hr)** | 29 | **OUTQ Area (m²)** | 113 | **OUTRIP Q Ttp (hr)** | 19.25 |
| **Avg Intensity (mm/hr)** | 1.11 | **Coull Ttp (hr)** | 23.75 | **INRIP soil Ttp (hr)** | 4 |
| **Max Intensity (mm/hr)** | 6.67 | **Aboyne Ttp (hr)** | 26 | **OUTRIP soil Ttp (hr)** | 19.5 |
| **API30 (mm)** | 31 | **Land Use** | Upslope: all tall crop (10)<br>Adjacent: all tall crop (6) | | |

Figure 5.10. Time series, event conditions and runoff conditions for event 367.

### *5.2.8 Field observations*

During a heavy rainfall event on 27 January 2014 (20 mm pcp depth), which is included as a runoff event in the preceding results (event 27,Table 5.1 and Table 5.6), the experiment equipment only captured part of the event. However, a field visit to replace the battery, which caused the loss of data, allowed field observations and photographs to be taken of overland flow paths. An overland flow path meandered through the centre of the riparian buffer strip. The source of this flow path was from overland flow coming from the adjacent field but entering the buffer strip further upstream of the experiment at a field gate. Runoff was observed to be flowing through the OUTRIP V-flume, but not the INRIP V-flume. The source of the OUTRIP V-flume was from a flow path running in parallel with the buffer strip, created by the tramline of the agricultural machinery previous driven over the area, which is clear in Figure 5.11. Despite this parallel flow, the runoff entered the OUTRIP V-flume because of the depth of the flow in tramline, spilling over into the buffer strip. This flow path led to the bottom corner of the field and ponded there (shown in Figure 5.11) before flowing into a field drain and directly back into the stream. The overland flow in the adjacent field was observed to be taking the path of least resistance, which in this case was the tramline forming a small channel. These observations emphasised the role of microtopography both through the centre of the buffer strip and in the adjacent field.

Battery failure was the result of being unable to record the flooding that occurred during extreme winter flooding in December 2015 and January 2016 where the Dee catchment experienced 2-4 times the average December rainfall (Met Office, 2016b). A field visit the morning after the January 2016 event provided similar evidence to the 27$^{th}$ January event (compared in Figure 5.11). The overland flow paths in the adjacent field are shown to run parallel with the riparian buffer strip, pooling in the bottom corner of the field. Photograph B and D in Figure 5.11, which are of the 2016 event, also indicate that there is an additional flow path, closer to the buffer strip edge. This flow path is taking the path of least resistance and seems unable to enter the buffer strip because of the barrier of the vegetation and slightly raised micro-topography at the edge of the buffer strip. Observing these flow paths prompted an assessment of whether the 1 m resolution DTM could predict these flow paths using ArcGIS flow path accumulation function. These results are outlined in Section 5.2.9.

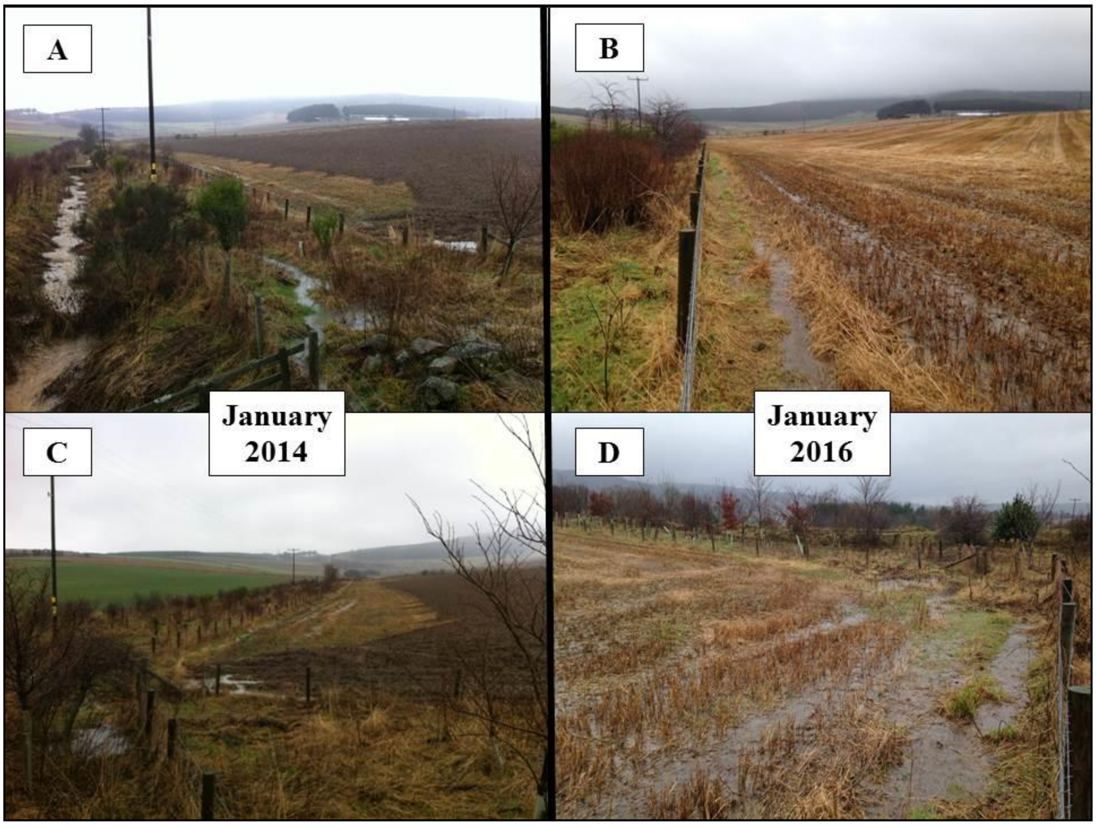



Figure 5.11. Photographs taken during two heavy rainfall events (January 2014 and January 2016). Evidence of overland flow pathways through the riparian buffer strip in January 2014. Both scenes show runoff being diverted from the buffer strip and pooling at the downslope field corner.

In addition, the time-lapse field camera captured the resulting runoff entering the buffer strip during the January 2016 event (Figure 5.12) and the December 2015 (Figure 5.13) event. Both photographs show the V-flume to be relatively full, demonstrating that overland flow entered the riparian buffer strip during these extreme events.


Figure 5.12. Time lapse camera capture of the OUTRIP V-flume during the January 2016 storm event. The depth of runoff in the OUTRIP V-flume can be seen at the bottom right corner.


Figure 5.13.Time lapse camera capture of the OUTRIP V-flume during the December 2015 storm event. The depth of runoff in the OUTRIP V-flume can be seen at the bottom right hand corner.

### 5.2.9 *Flow accumulation pathways derived from a digital terrain model*

Flow accumulation pathways (Figure 5.14) were assessed in response to the field observation to determine whether the 1 m DTM could predict the influence of the micro-topographies that were directing overland flow. This assessed whether these flow paths would be predicted in the same location as those observed in the field.

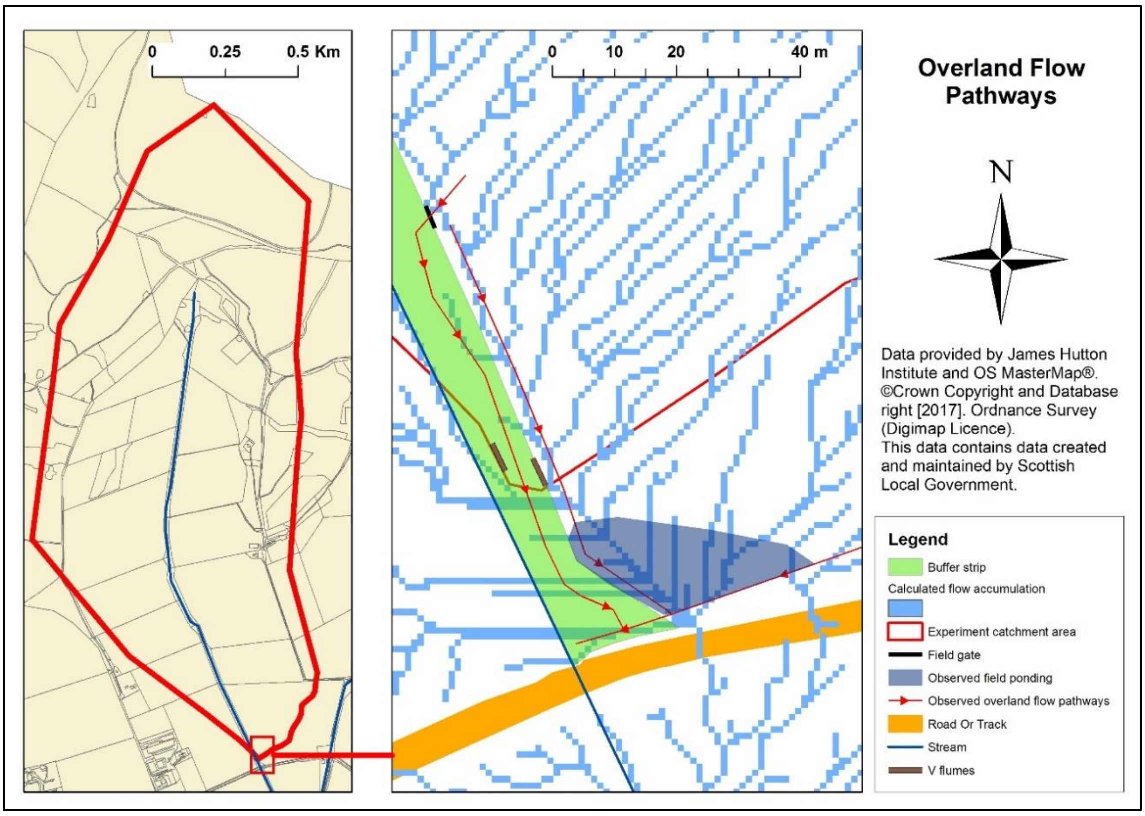



Figure 5.14**.** Comparison between flow accumulation pathways using 1 m resolution and observed overland flow pathways (from January 2014 and January 2016). The overland flow pathway through the centre of the buffer strip was observed only in January 2014. Other pathways were evident on each occasion.

Figure 5.14 compares the flow accumulation pathways using the DTM and field observations of overland flow pathways (highlighted in red). Those derived from the DTM are relatively close to those observed in the field showing overland flow paths collect at the field corner. However, the stream is not well represented and appears to be shifted as though it is situated at the adjacent field next to the boundary of the buffer strip. This demonstrates that the flow paths observed in the field cannot be represented with the 1 m resolution DTM but may be more accurate with a higher resolution. This clarifies the requirement for ground-truthing at field sites and highlights the errors that can be within a 1 m resolution DTM.

## 5.3 Research question 2 results: introduction

*RQ2: What is the impact of riparian buffer strips on algae biomass in streams as an indicator of nutrient cycling and primary production?*

The following sections in this chapter outline the results that address RQ2. The EQR is firstly determined for the buffered and non-buffered site. The ES framework is subsequently presented and its functionality described but is further discussed in Chapter 7 in relation to the EQR and other results for RQ2. Mann-Whitney results are outlined and in conjunction with the graphical analysis of median Chl-a concentrations at each site, specific months are identified that require further assessment using supporting results. These are obtained from the assessment of land management (buffered site only), field observations, nutrient data (buffer site only), and weather statistics.

### *5.3.1 Comparison of Ecological Quality Ratio for Chlorophyll-a*

The purpose of the EQR assessment was to establish the status that would be attributed to the buffered and non-buffered study sites based on algae concentrations (measured by Chl-a) and compare. The buffered site had a slightly higher EQR (0.24) compared to the non-buffered site (0.20), but both sites are determined as *moderate* status (Table 5.13) based on the WFD-UKTAG (2014) methodology. The Scottish Environment Protection Agency (SEPA) classifies water bodies as a whole and the Tarland Burn was considered *good* for aquatic plants, *high* for reactive phosphorus (which affects algae growth), and *moderate* for fish ecology (Table 5.13) in 2017 (the latest WFD assessment period) (SEPA, 2017). The buffered and non-buffered streams are tributaries to the Tarland Burn whereas; SEPA's status accounts for the whole catchment. In terms of algal biomass (measured by Chl-a concentration), both the buffered and non-buffered sites could be improved to achieve *good* status. If the sites were to deteriorate to *poor* status, this could impact on fish ecology, which is currently *moderate*. The impact of the EQR and status of the Chl-a concentrations are explored further in Section 5.3.2 below.

Table 5.13. Status of buffered and non-buffered stream based on chlorophyll-a ecological quality ratio ($EQR_{Chl}$) using WFD-UKTAG (2014) methodology compared to SEPA Tarland Burn status for aquatic plants, reactive phosphorus and fish ecology.

<table>
<tr><th>Site</th><th>Annual geometric mean Chl-a</th><th>EQR<sub>Chl</sub></th><th>Status</th><th>SEPA aquatic plant status</th><th>SEPA reactive phosphorus status</th><th>SEPA fish ecology status</th></tr>
<tr><td>Buffered</td><td>22.3</td><td>0.24</td><td>Moderate</td><td rowspan="2">Good</td><td rowspan="2">High</td><td rowspan="2">Moderate</td></tr>
<tr><td>Non-buffered</td><td>26.5</td><td>0.20</td><td>Moderate</td></tr>
</table>

A description of the Chl-a status and its conditions (in lakes) is provided by WFD-UKTAG (2014) and summarised in Table 5.14. These conditions are outlined for lakes, which was the methodology adopted due to lack of phytoplankton assessment for lotic systems. As highlighted in Section 3.4.5, there is uncertainty in status attribution to the study sites and the conditions of this status for lakes are outlined in Table 5.14. However, phytoplankton are widely known to respond to nutrients, temperature, light, and precipitation/runoff inputs, regardless of their water body type

(Royer et al., 2008). Albeit mixing, residence times and stratification (lakes only) of nutrients are different between lentic and lotic systems. The *moderate* status description in Table 5.14 indicates a moderate imbalance in algae biomass may be affecting the water and biological quality of the stream. The annual geometric mean Chl-a would need to reach 17.5 µg/L to achieve *good* status with an EQR of 0.3. The non-buffered and buffered site would need to reduce its geometric mean of Chl-a by 9 µg/L and 4.8 µg/L, respectively (Table 5.13). Despite both being classed as *moderate* status, this clarifies that the non-buffered site requires a greater reduction in algae biomass than the buffered site to achieve *good* status; indicating the riparian buffer strip site has slightly better algae biomass conditions.

Table 5.14. WFD-UKTAG (2014) description of chlorophyll-a (phytoplankton) conditions, as per the Water Framework Directive, for high, good and moderate status. These conditions are relevant to lakes but are used to understand likely conditions in lotic systems in the absence of river-based phytoplankton classification frameworks.

| HIGH STATUS | GOOD STATUS | MODERATE STATUS |
|---|---|---|
| The taxonomic composition and abundance of phytoplankton correspond totally or nearly totally to undisturbed conditions.<br><br>The average phytoplankton biomass is consistent with the type-specific physico-chemical conditions and is not such as to significantly alter the type-specific transparency conditions.<br><br>Planktonic blooms occur at a frequency and intensity which is consistent with the type specific physico-chemical conditions. | There are slight changes in the composition and abundance of planktonic taxa compared to the type-specific communities. Such changes do not indicate any accelerated growth of algae resulting in undesirable disturbance to the balance of organisms present in the water body or to the physico-chemical quality of the water or sediment.<br><br>A slight increase in the frequency and intensity of the type-specific planktonic blooms may occur. | The composition and abundance of planktonic taxa differ moderately from the type-specific communities.<br><br>Biomass is moderately disturbed and may be such as to produce a significant undesirable disturbance in the condition of other biological quality elements and the physico-chemical quality of the water or sediment.<br><br>A moderate increase in the frequency and intensity of planktonic blooms may occur. Persistent blooms may occur during summer months. |

### *5.3.2 Ecosystem services framework for algae*

In this section, a summarised framework of the role of Chl-a (algae) in the provision of ES is outlined using a pictographic framework. The purpose of this framework is to provide an overview of the complex relationships between the ecological and biological functions of algae and how they factor into ES provision. It will enable a reference point for interpreting the possible impacts of the EQR and status of the study sites, as well as for discussion of the algae results in Chapter 7. Distinctions of the framework are outlined below but more details on the ES of algae are provided in the literature review in Chapter 2.

The Chl-a influences in Figure 5.15 indicate elements that can impact Chl-a concentrations. Fertilisers for example, can enhance nutrient availability for Chl-a growth. These influences are also interlinked. Land management regimes will dictate the volumes of fertiliser application and the soil conditions. The soil conditions can affect nutrient and fertiliser transport in which weather conditions (rainfall) and flow regimes in streams have a role in the velocity of transportation and residence times of nutrients in streams. The requirements of Chl-a (Figure 5.15) indicate further environmental aspects that can affect their concentration. Higher temperatures and sunlight, carbon dioxide and nutrients are all linked to Chl-a concentrations. Riparian buffer strips have a role in minimising Chl-a influences and assisting in the balance of Chl-a requirements to limit Chl-a concentrations to levels that are safe and ecologically productive.

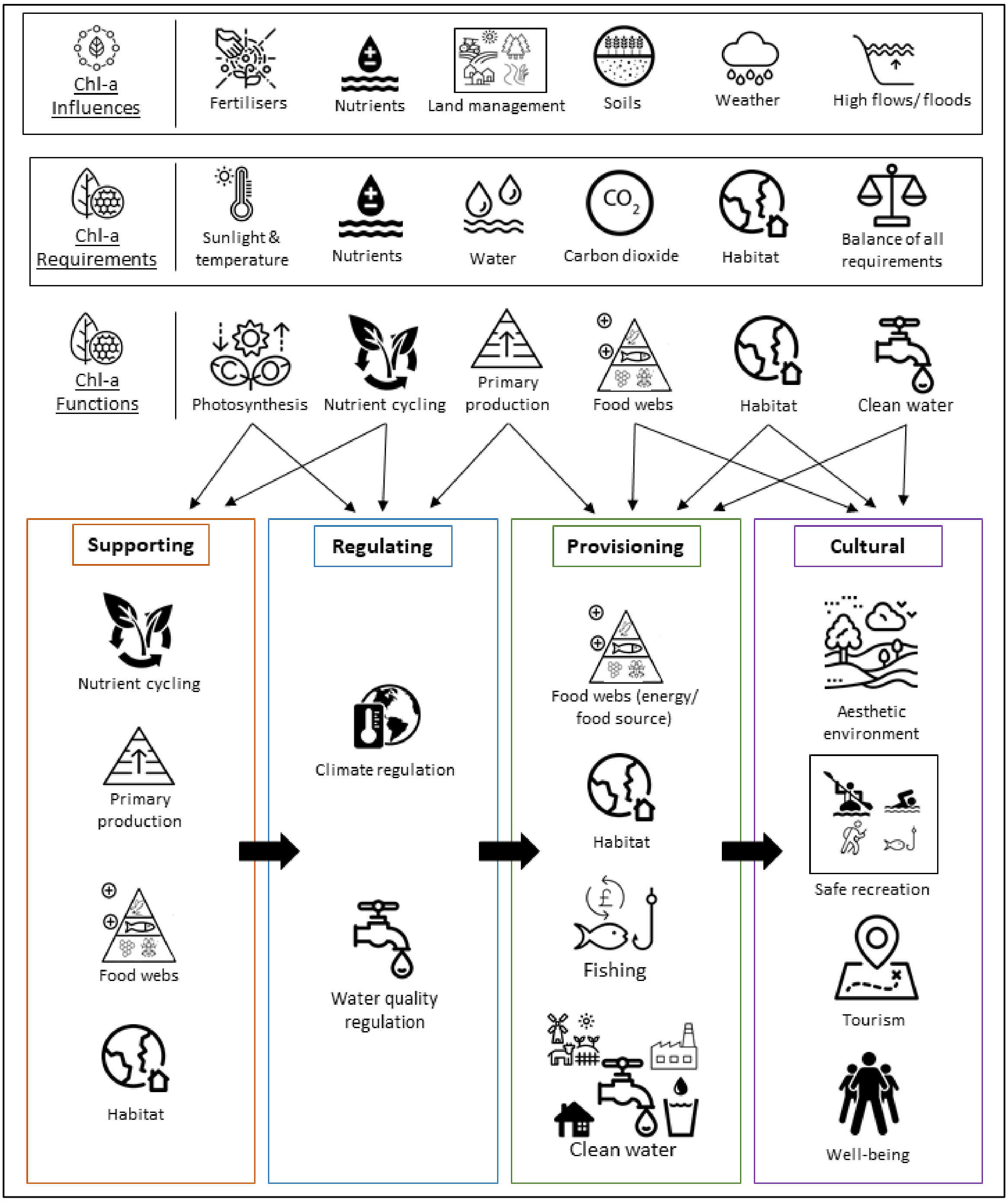



Figure 5.15. Pictographic framework of influences, requirements and functions of Chl-a (algae) and linkages between Chl-a functions and supporting, regulating, provisioning and cultural ecosystem services. Chl-a functions and their direct role in each ES type are identified by slim arrows. The cascade of influence of the types of ES provided by Chl-a are identified with thick arrows. Created using images from thenounproject.com.

The functions of Chl-a (Figure 5.15) are indicative of the ES they can influence either directly or indirectly. The linkages between these ES are represented in the framework to allow inference of how Chl-a concentrations could have a knock-on effect or a more direct impact on ES provision. For example, photosynthesis and primary production (supporting ES) are directly impacted by the functions of Chl-a (photosynthesis and nutrient cycling) but these have an indirect effect on regulating the climate and providing safe habitat for higher trophic levels of an ecosystem.

The framework (Figure 5.15) is essential a visual tool that represents literature and how Chl-a concentrations have linkages to ES. It will be used in the discussion to make linkages between the findings of this study and implications of these findings for wider ES.

### *5.3.3 Mann-Whitney results: statistical difference between algae concentrations in a buffered and non-buffered stream*

The purpose of the Mann-Whitney statistical test was to ascertain whether the concentrations of algae are statistically different between a riparian buffer strip stream and a stream with no buffer. A comparison between median Chl-a concentrations each month where data existed for both sites is summarised in Table 5.15. A spatial visualisation of individual Chl-a concentrations measured for all 33 sample sites along each 50 m reach is shown in Appendix 11. The values in Appendix 11 are the individual values used to derive the median Chl-a values for each month.

Table 5.15. Mann-Whitney statistical results determining the statistical difference (Diff.) between median chlorophyll-a (Chl-a) at the riparian buffer strip (Rip) and site with no riparian buffer strip (No rip). Months highlighted show those with a significant difference (*P*-value <0.05). Chl-a is measured in µg/l. Catchment wetness at the time of sampling is demonstrated by 30-day antecedent precipitation index (API30) and the number of rainfall events with a depth occurring 5% of the time (No. Q5 rain events).

| *Year* | *Season* | *Month* | *No rip median* | *Rip median* | *Diff.* | *P-value* | *API30* | *No. Q5 rain events* |
|---|---|---|---|---|---|---|---|---|
| 2014 | Spring | Apr | 33.1 | 36.9 | -4.5 | 0.008 | 10.8 | 0 |
| 2014 | Spring | May | 25.7 | 27.9 | 4.3 | 0.276 | 25.3 | 1 |
| 2014 | Summer | Jun | 36.1 | 36.3 | 0.2 | 0.972 | 31.9 | 0 |
| 2014 | Summer | Aug | 9.7 | 3.4 | 5.9 | 0.017 | 58.3 | 5 |
| 2014 | Autumn | Sep | 34.6 | 28 | 3.7 | 0.256 | 28.5 | 1 |
| 2014 | Autumn | Oct | 23.4 | 1.1 | 4 | 0.109 | 53 | 3 |
| 2014 | Autumn | Nov | 4.5 | 1.7 | 1.6 | 0.027 | 42.5 | 4 |
| 2015 | Winter | Feb | 10 | 1.8 | -0.2 | 0.797 | 13.4 | 0 |
| 2015 | Spring | Mar | 14.5 | 4.8 | 4.4 | 0.087 | 14.2 | 0 |
| 2015 | Spring | May | 33.8 | 15.4 | 7.4 | 0.112 | 32.6 | 2 |

All monthly comparisons show there is a difference in Chl-a concentrations between the buffered and non-buffered site (Table 5.15). However, only three months show this difference to be statistically significant (*P*-value <0.05): April 2014, August 2014, and November 2014 (Table 5.15). The difference in monthly median values indicate the riparian buffer strip site to have a higher median than the non-buffered site in April 2014 (also shown to be statistically significant) and in May 2014. The remaining months show the non-buffered site to have the highest median. These median Chl-a concentrations for each site are explored further in Section 5.3.4 and outlines supporting data that may indicate why these differences occur.

### *5.3.4 Graphical analysis: comparison of algae concentrations in a buffered and non-buffered stream*

The purpose of the following graphical analysis is to assess any trends in Chl-a concentrations between the buffered and non-buffered streams for each month where data exists for both sites. Concurring with the results in Section 5.3.3, the riparian buffer site shows a higher median concentration of Chl-a than the non-buffered site in April and May 2014 (Figure 5.16) but is consistently lower after May 2014.

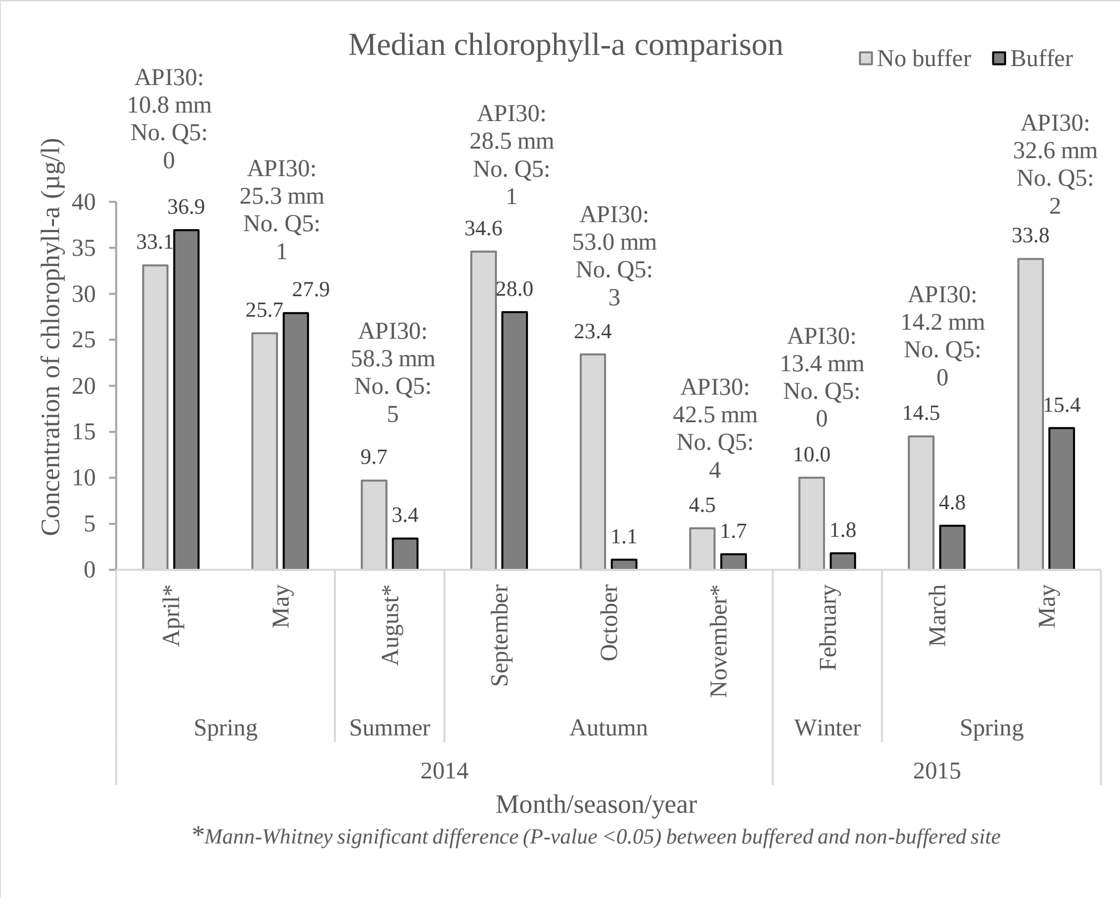



Figure 5.16. Monthly comparison of median chlorophyll-a concentrations for the buffered and non-buffered sites. Those determined as being significantly different in the Mann-Whitney statistical test are denoted by *. The 30-day antecedent precipitation index (API30) and number of rainfall event depths occurring 5% or less of the time (No. Q5) inform the catchment wetness conditions at time of sampling.

The greatest difference in Chl-a concentrations between the buffered and non-buffered site is shown in October 2014 (1.1 µg/l and 24.1 µg/l respectively), yet this difference is not statistically significant (Table 5.15).

Algae concentrations would be expected to be higher in warmer months (spring and summer), reducing throughout autumn and winter before increasing again in Spring. However, the following irregularities occur (Figure 5.16):

- The buffered site shows a seasonal trend with exception to September 2014 when Chl-a concentrations are much higher (28 µg/l).
- The non-buffered site shows a seasonal trend but a marked increase in Chl-a concentrations in September (34.6 µg/l) and October (23.4 µg/l). From November 2014 to May 2015 algae concentrations are gradually increasing, reflecting seasonal changes.

The evident seasonal trend from November 2014 to May 2015 (Figure 5.16) demonstrates the Chl-a concentrations at the non-buffered site to increase at a higher rate than the buffered site each site: the difference between the sites increases each subsequent month from November.

Further supplementary results (Section 5.3.5) on land management, weather, nutrients and field observations will be examined to explore any trends that could indicate reason for the aforementioned peculiarities.

### *5.3.5 Supplementary results*

This section outlines additional data that aims to explore reasons for the findings in Section 5.3.4. Specifically, these results will focus on aspects which consider:

a) The buffered site having a higher Chl-a concentration for the first two months (April and May 2014), but the non-buffered site being higher thereafter.
b) The high median Chl-a concentrations in September 2014 (both sites) and October 2014 (non-buffered site only) that deviate from the seasonal trends. The greatest difference in median Chl-a concentrations is also in October 2014.
c) The non-buffered site's seasonal rise in Chl-a concentrations are incrementally higher than the buffered site.

Subsequent sections utilise land management practices, weather data, nutrient monitoring data and field observations to provide focused results to address the elements outlined above. The land management and nutrient sections apply only to the buffered site (as the data only exists for this site).

**<u>Land management changes (buffered site)</u>**

Land management changes in the adjacent and upslope agricultural fields at the riparian buffer strip were assessed using monthly field photographs (originally obtained for the runoff experiment, see Section 5.2.1). Minimal photographs exist for the non-buffered site but the few that do exist are used in the *Field observations* section. The monthly photographs (buffered site) were transcribed into a schematic of each field in relation to the algae sampling transect, which describes the vegetative conditions as: bare soil, tall crop, short crop, or pasture (Figure 5.17).

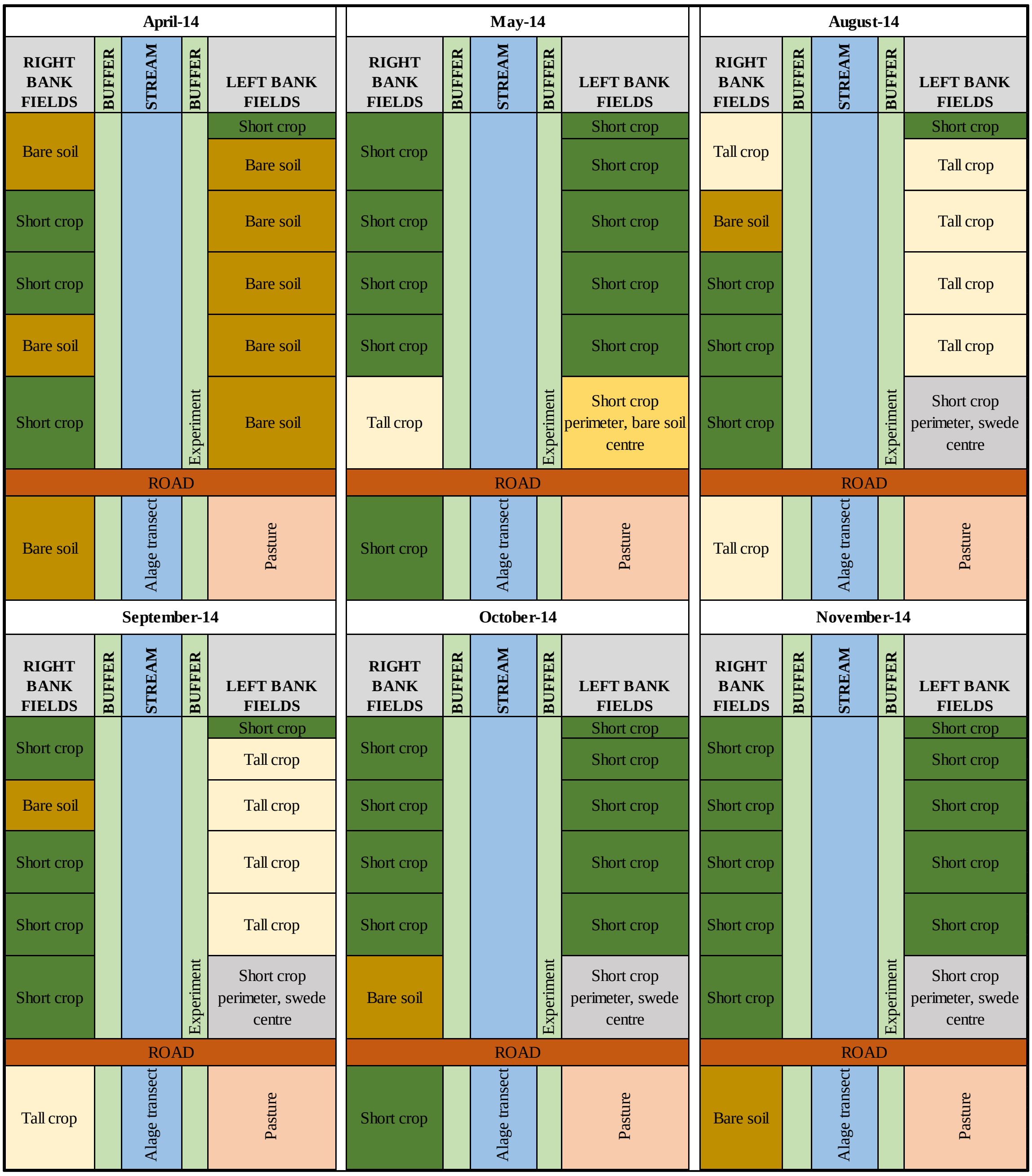



Figure 5.17. Schematic of monthly land management in fields upstream of the algae torch sample site at the riparian buffer site based on monthly field photographs. Not to scale.

The purpose of assessing the land management changes at the riparian buffer strip site is to ascertain whether any trends in Chl-a concentrations coincide with relevant land management changes. The key results are listed below:

- High Chl-a in April and May 2014
    - Land management at the riparian buffer site is shown to have the greatest extent of bare soil in April 2014 (Figure 5.17), which may be having an influence on the higher Chl-a concentrations.

  - However, this coincidence is not consistent. In May and September 2014 there is more vegetation (Figure 5.17); indicating there may be other factors influencing the Chl-a concentration peaks.
- High Chl-a in September 2014
  - In September 2014 vegetative cover is extensive with five fields with tall crop, five with short crop and only one with bare soil (Figure 5.17).
- Very low Chl-a in October 2014
  - In October 2014, Chl-a concentration is at its lowest at the buffered site. The five fields of tall crop have been harvested in October and now consist of short crop (Figure 5.17).

These results demonstrate there are no trends in land management which reflect the Chl-a concentrations. However, they may be an influencing factor alongside the subsequent weather and nutrient results.

**Weather influences**

Weather variables are examined to highlight any trends that may influence the Chl-a concentrations at the buffered and non-buffered site. The results are listed below:

- High Chl-a in April and May 2014 (buffered site)
  - Precipitation and temperature show an inverse trend to the Chl-a values at both sites in April and May 2014, but this trend is not reflected throughout the remaining experiment period (Figure 5.18).
- High Chl-a in September 2014 (both sites).
  - The higher Chl-a concentrations at the buffered and non-buffered sites in September coincide with the highest mean daily temperature (13.8 °C) and simultaneous reduction (from August) in 30-day precipitation (60.3 mm, Figure 5.18) and reduction in API30 (28.5 mm, Table 5.16). But these observations do not translate to other months.
  - Other variables are likely influencing the Chl-a concentrations.
- October 2014: high Chl-a at the non-buffered site and low Chl-a at the buffered site.
  - The 30-day depth of precipitation and mean daily temperature (on the day of measurement) reflect the seasonal trend at both sites from February to May 2015, but this trend is not reflected in November 2014 (Figure 5.18). This indicates other variables are having an influence in November 2014.

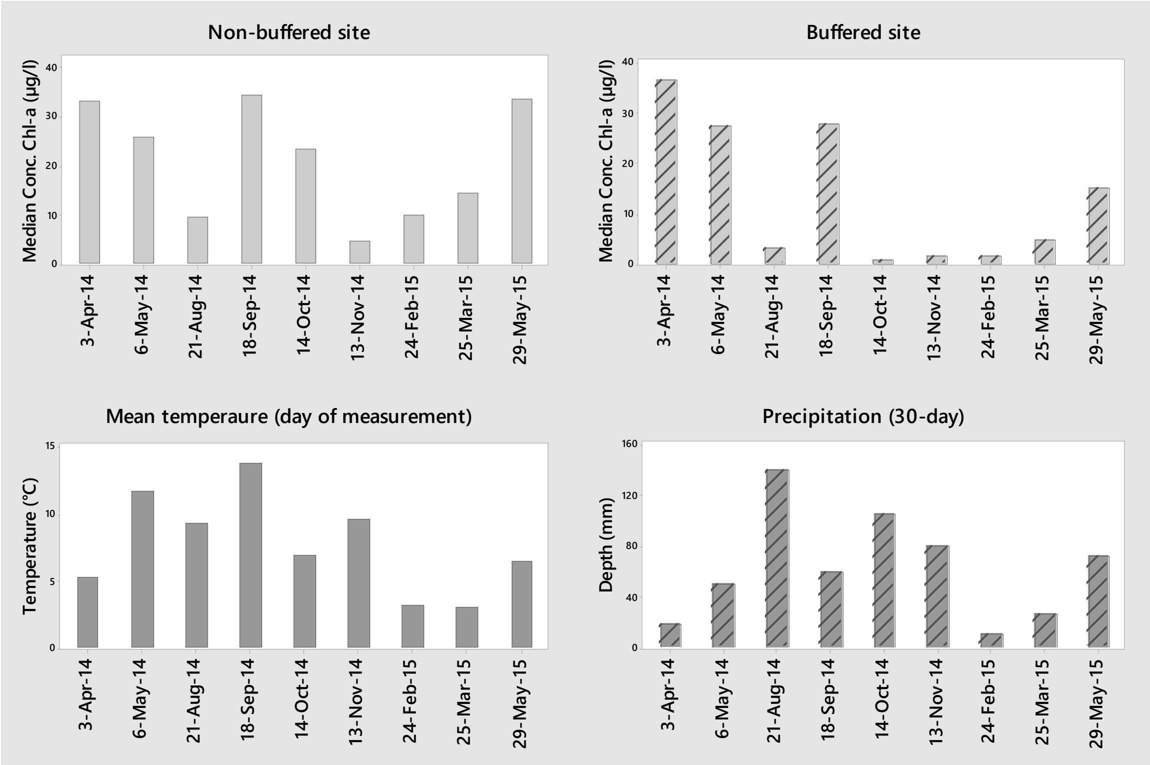


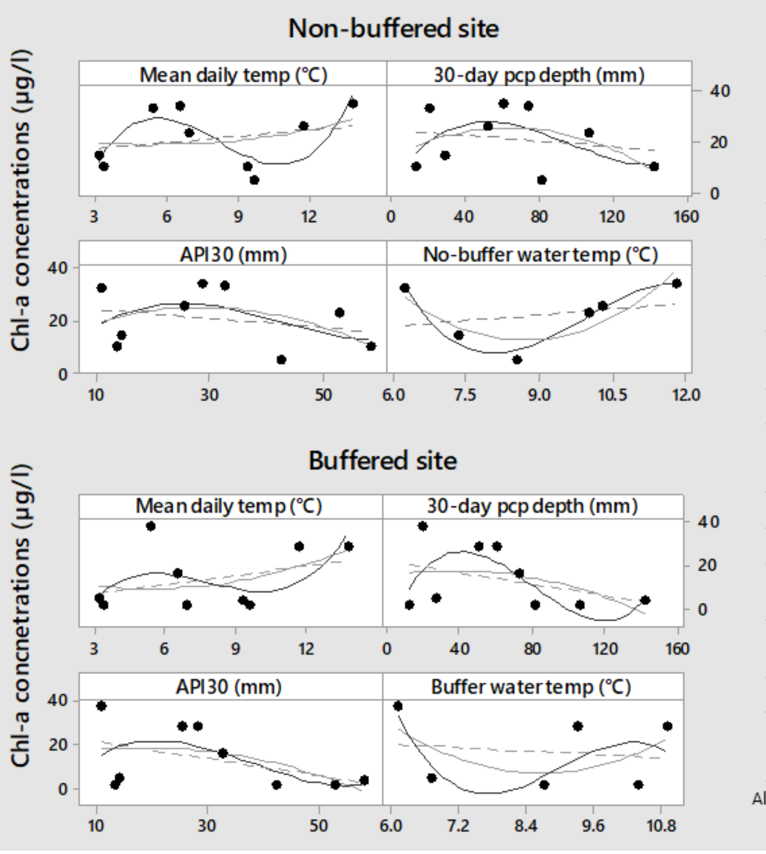

Figure 5.18. Graphical representation of median Chl-a concentrations at the buffered and non-buffered site compared to the total precipitation depth for the previous 30 days and mean temperature for the day of algae torch measurement.

Table 5.16. Weather characteristics, counts of Q5 events, and water temperature for each month of Chl-a measurement at each site. The 30-day precipitation depth (30-day pcp) and counts of rainfall events are calculated for the preceding 30 days from algae torch measurement. Temperatures are from the day of measurement.

| ***Month*** | ***30-day pcp depth (mm)*** | ***API30 (mm)*** | ***Count rainfall events Q5*** | ***Min temp*** | ***Max temp*** | ***Mean temp*** | ***Buffer site water temp*** | ***No-buffer site water temp*** |
|---|---|---|---|---|---|---|---|---|
| Apr-14 | 19.5 | 10.8 | 0 | 4.4 | 6.8 | 5.3 | 6.1 | 6.2 |
| May-14 | 50.7 | 25.3 | 1 | 9.1 | 15.8 | 11.7 | 9.3 | 10.3 |
| Aug-14 | 142.2 | 58.3 | 5 | 6.8 | 13.6 | 9.3 | | |
| Sep-14 | 60.3 | 28.5 | 1 | 13.1 | 15.5 | 13.8 | 10.9 | 11.8 |
| Oct-14 | 106.0 | 53.0 | 3 | 4.5 | 10.0 | 6.9 | 10.4 | 10.0 |
| Nov-14 | 81.0 | 42.5 | 4 | 8.1 | 11.3 | 9.6 | 8.7 | 8.5 |
| Feb-15 | 12.3 | 13.4 | 0 | -1.0 | 6.5 | 3.3 | | |
| Mar-15 | 27.4 | 14.2 | 0 | -1.0 | 8.6 | 3.1 | 6.7 | 7.3 |
| May-15 | 72.8 | 32.6 | 2 | 3.1 | 12.5 | 6.5 | | |

Overall, weather trends are contradictory: when conditions are explained for one Chl-a scenario, this same trend is not reflected in other months. When compared to the land management results, the buffered site Chl-a concentration reduces dramatically in October 2014 when five fields have been harvested (Figure 5.17). This coincides with high API30 (53 mm), high precipitation depth (81 mm), and three Q5 events (pcp depth >16.1 mm) and would likely result in runoff from the surrounding harvested landscape. These results indicate other variables to be influencing Chl-a concentrations in October 2014.

Regression relationships were explored and showed cubic (polynomial) relationships between Chl-a and weather variables to have the best fit (Figure 5.19Figure 5.19). The non-buffered site has the best cubic regression fit between Chl-a and mean daily temperature ($R^2$ 0.67) and water temperature ($R^2$ 0.95) (Figure 5.19). Only the mean daily temperature and Chl-a relationship is significant (*P*-value 0.03 and 0.09, respectively, Figure 5.19). The strong ($R^2$ 0.67) significant (*P*-value 0.03) positive cubic relationship between mean daily temperature and the non-buffered Chl-a explains the seasonal increase in Chl-a from February to May 2015. The same relationship is weaker ($R^2$ 0.36) and not significant (*P*-value >0.05) at the buffered site. The non-buffered site has a better cubic regression fit to weather variables than the buffered site (Figure 5.19).




| $R^2$ | Linear | Quad. | Cubic |
|---|---|---|---|
| **Non-buffered site** | | | |
| Mean Temp | 0.06 | 0.08 | 0.67* |
| 30-day pcp | 0.04 | 0.21 | 0.24 |
| API30 | 0.07 | 0.18 | 0.19 |
| Water temp | 0.07 | 0.72 | 0.95 |
| **Buffered site** | | | |
| Mean Temp | 0.13 | 0.18 | 0.36 |
| 30-day pcp | 0.20 | 0.15 | 0.43 |
| API30 | 0.22 | 0.27 | 0.30 |
| Water temp | 0.02 | 0.24 | 0.39 |

All p-values >0.05 (not significant relationship) except *(p-value 0.03)

Figure 5.19. Chlorophyll-a regression relationships with precipitation, API30 and temperature for the buffered and non-buffered sites. Cubic, linear and quadratic relationships are tested and $R^2$ values shown. Note that there are <20 sample points and relationships therefore require more data to be reliable.

**Nutrients**

Nutrient monitoring for $NH_4$-N, $NO_3$-N, Total-N, $PO_4$-P, Total-P and DOC are examined in relation to the Chl-a concentrations at the buffered site. This assessment aims to understand relationships between nutrients and Chl-a at the buffered site, as well as examine trends in monthly measurements.

All nutrients are shown to decrease from April to May 2014 (Figure 5.20) showing a similar trend to the decrease in Chl-a. But their increase in August does not reflect the low Chl-a concentration in August. But this does coincide with significantly higher 30-day pcp (142.2 mm) and the highest number (5) of Q5 events (Table 5.16), despite land conditions having substantial fields of tall crop (Figure 5.17). The missing nutrient data in October 2014 prevents assessment of nutrient influence on the reduction of Chl-a in October 2014.

Relationships between Chl-a and nutrients show Total-N, DOC and $NO_3$-N to have a negative cubic relationship (Figure 5.21) and Figure 5.20 reflects this in the time series as Total-N, DOC and $NO_3$-N decline when there is a seasonal in increase in Chl-a.

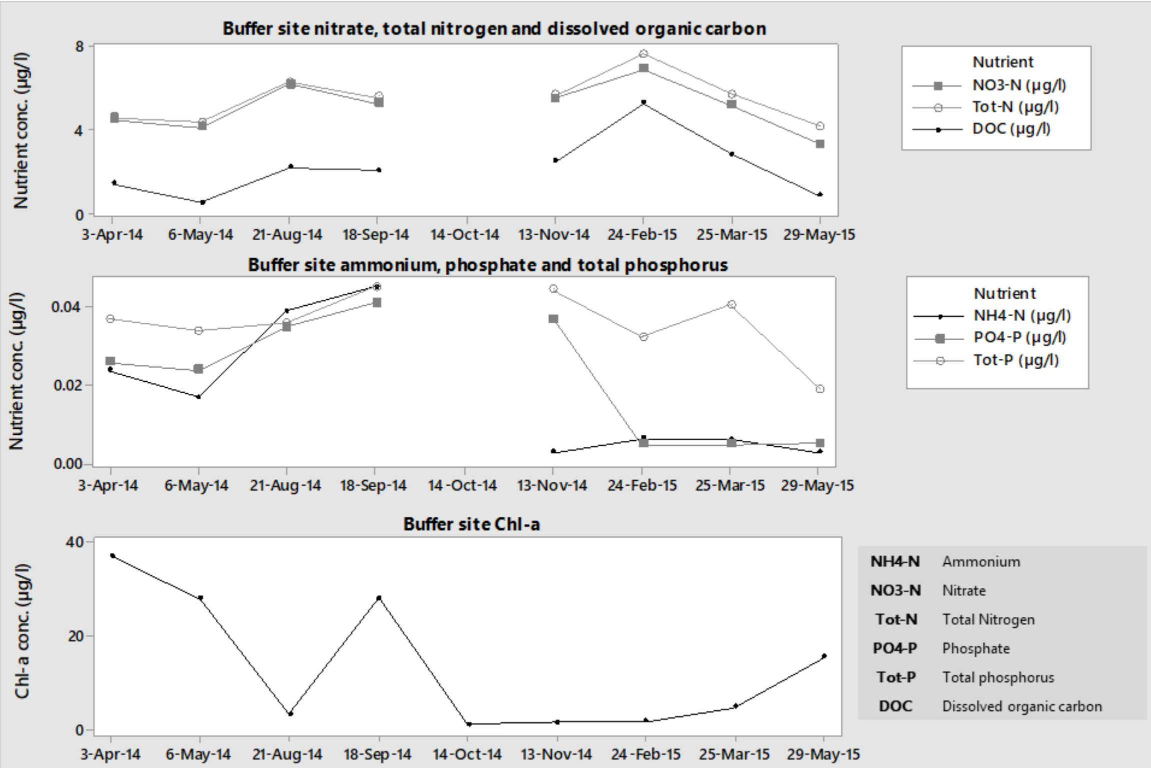



Figure 5.20. Comparison of time series of Chlorophyll-a and nutrients at the buffered site. October 2014 nutrient data is missing

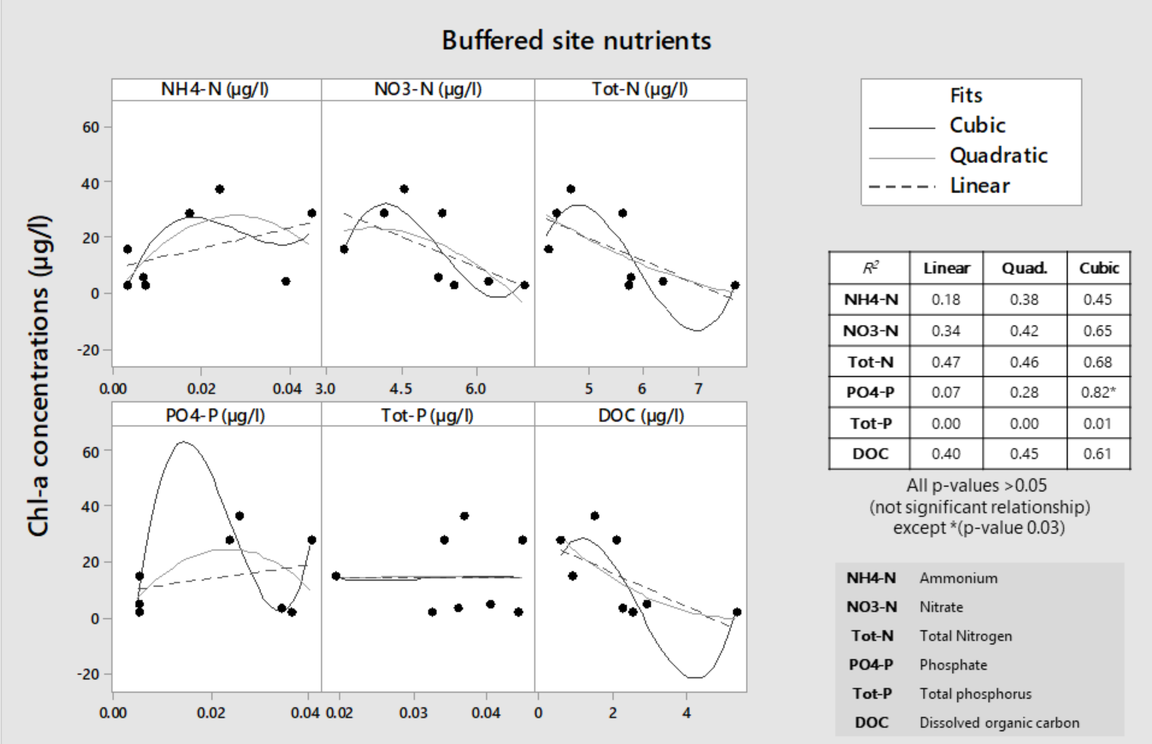



Figure 5.21. Chlorophyll-a regression relationships with nutrients at the buffered site. Cubic, linear and quadratic relationships are tested and $R^2$ values shown. Note that there are <20 sample points and relationships therefore require more data to be reliable.

**Field observations**

During each field visit, observations of any aspect that may affect the algae concentrations were recorded. The only relevant observations were obtained in August 2014, which coincides with a dramatic reduction in algae concentrations at both the buffered and non-buffered sites (Figure 5.16).

At the riparian buffer strip site, water levels were elevated, and channel morphology had changed due to vegetation debris that had washed downstream creating new pools and backing up flows. At the non-buffered site however, between transects 4 and 5 (Figure 3.14 and Section 3.4.4), the channel had been significantly disturbed as the land owner had used mechanical means to dig out the left bank to reinstate the flow of tile drain (left picture of Figure 5.22). Flow from this tile drain was now entering the stream. Significant poaching by livestock was observed from August 2014 (Figure 5.22) at the road culvert and further downstream at the first and second downstream transect.


Figure 5.22. Photographs of the non-buffered site in August 2014 following alteration to channel to reinstate a tile drain (left picture) and showing evidence of bank poaching by livestock (right picture).

## 5.4 Chapter summary

This research aimed to understand the effectiveness of riparian buffer strips as an NFM measure. This chapter presented results that outline conditions by which overland flow entered the riparian buffer strip thereby providing attenuation of surface runoff. It also provided findings of an assessment of the multiple benefits of riparian buffer strips as an NFM measure by examining their impact on algae concentrations. The linkages between algae (measured as Chl-a) and ES are illustrated. A summary of the findings for each RQ are outlined below.

**RQ1 What are the different conditions by which overland flow moves into and through riparian buffer strips?**

- Overland flow is determined to be generated through saturation excess based on a comparison of the infiltration rate of the adjacent field and the maximum hourly catchment precipitation intensity.
- The adjacent field is dominated by a swede crop in the centre of the field (ploughed downslope) with a perimeter of tall hay or short grass (once harvested). There are two instances where the adjacent field consists of bare soil. The latter months of the experiment is when the adjacent field is a crop of barley with no perimeter. The land categories analysed in more detail in relation to runoff events occurring in the riparian buffer strip are:
    - A1: short crop perimeter, bare soil centre
    - A4: Short crop perimeter, swede crop centre
    - A6: All tall crop
    - A7: no data (harvested estimated by end of September 2015)
- Mann-Whitney tests reveal there is no significant difference between infiltration and runoff events and their associated event conditions (pcp depth, duration, intensity, maximum intensity, and API30).

- Out of twenty-three 'events' identified, nine were runoff events, three were infiltration events and eleven were rejected. Subsequent analysis excluded one infiltration event as an experimental error.
- Trend analysis of event conditions found:
    - API30, pcp depth and maximum intensity event conditions best explained why runoff would enter the riparian buffer strip.
    - Runoff events occurred when:
        - Pcp depth ≥20 mm; if < 20 mm runoff would occur if API30 was high (e.g ≥70 mm) and or/max intensity was high (e.g. ≥3.2 mm).
        - API30 ≥29 mm; if <29 mm runoff would occur when Pcp depth ≥23.9 mm and max intensity ≥ 3.7 mm.
        - Max intensity >1.8 mm; no runoff occurred when API30 was low (e.g. ≤21 mm) and max intensity was >1.8 mm.
        - Event duration was ≥47 hr; if <47 hr runoff would occur if API30 was high (e.g. ≥31 mm) and/or max intensity was high (≥3.2 mm)
- Trend analysis of land management and event conditions found:
    - The study was unable to differentiate if land management or event conditions were more influential on runoff Qpk, runoff volume and runoff contributing area than the other. Limited data for statistical analysis restricted this assessment to trends only.
    - Bare soils coincided with the highest runoff Qpk, runoff volume and runoff contributing area but seemed to be exacerbated by the simultaneous impact of event conditions (API30, pcp depth and max intensity).
    - One instance of a runoff event occurred during summer when the adjacent field was a tall crop and API30 was low. Max intensity was the overarching event condition that indicated why runoff entered the riparian buffer strip.
- Results pertaining to field observations and flow paths included:
    - Concentrated overland flow paths were observed through the centre of the riparian buffer strip during one heavy rainfall event.
    - Microtopography as a result of tramlines, farm traffic and plough lines were observed to divert overland flow away from the riparian buffer strip. However, when these flow paths reached a sufficient depth, runoff did spill into the riparian buffer strip.
    - Assessing a 1 m DTM flow accumulation paths illustrated a higher resolution would be required to pick up on such microtopographies but did indicate where the resulting pool of the overland flow would occur in the field corner.

**<u>RQ2 What is the impact of riparian buffer strips on algae concentrations in streams as an indicator of ecological quality and ecosystem services?</u>**

- The buffered and non-buffered sites both scored as being at *moderate* status using the EQR but differed in the annual geometric mean Chl-a where the non-buffered site was in a slightly worse condition.
- Mann-Whitney statistical tests determined Chl-a concentrations to be different between sites for all recorded months but only three months were statistically significant: April 2014, August 2014 and November 2014.
- Graphical analysis highlighted the following:
    - Seasonal irregularities where each site demonstrated the expected seasonal trends in Chl-a concentration, but September 2014 had high Chl-a at both sites and October 2014 had high Chl-a at the non-buffered site, interrupting the seasonal trend.
    - The seasonal increase of Chl-a increased at a higher rate at the non-buffered site and the difference between Chl-a concentrations at the buffered and non-buffered site grew larger as the concentrations increased.
- Supplementary results explored land management and nutrient data from the buffered site but also assessed weather influences and used field observations to support results at the buffered and non-buffered site:
    - Weather and land management trends were contradictory as where one set of conditions coincided with Chl-a concentrations it was not reflected for similar Chl-a concentrations in a different month.
    - However, the dramatic decrease in Chl-a at the buffered site in August 2014 coincided with five fields being harvested, high API30, high pcp depth and three preceding Q5 events. These conditions are indicative of high flows and more runoff which could lead to flushing of the Chl-a.
    - The non-buffered site showed the strongest relationship with mean daily temperature and stream temperature, but all relationships tested were based on a sample of <20 and cannot be conclusive.
    - Nutrient assessment indicated flow conditions likely had the overriding influence on Chl-a conditions as nutrient concentrations were elevated but the event conditions in August 2014 restricted Chl-a response. Despite Total-N, DOC and $NO_3$-N having a string negative cubic relationship with Chl-a concentrations at the buffered site, these were based on a sample of <20 and cannot be conclusive.
    - Field observations in August 2014 confirmed the elevated flows at both sites. At the non-buffered site part of the stream had been re-sectioned and dug out by the landowner to reinstate a tile drain. Livestock poaching of banks was also evident.

# Chapter 6 Modelling results

## 6.1 Chapter introduction

Modelling the impact of catchment-wide riparian buffer strips on the reduction of peak flows to reduce flood risk was undertaken to address RQ3:

**RQ3:** How effective are catchment-wide riparian buffer strips at reducing peak flow and what is the most effective riparian buffer strip width and vegetation type (using SWAT model as a tool)?

a. What width of catchment-wide riparian buffer strip reduces peak flow ($m^3/s$) most effectively at upper, middle and lower catchment scale?
b. Do grass-based or tree-based riparian buffer strips provide a greater reduction in peak flow?

The results generated by using SWAT were analysed to ascertain the effectiveness of each buffer scenario. This chapter outlines high flow event characteristics are summarised and identifies spatial coverage of land uses (including all grass-based and tree-based land uses) and soils to enable the consideration of why reduction in peak flow may be different at each spatial scale. Differences in percentage reduction of peak flow at the upper, middle and lower catchment scales are presented. An assessment of whether the size of the peak flow relates to the degree of peak flow reduction is illustrated. The most effective vegetation type (grass or trees) in the buffer scenarios is highlighted alongside a comparison of whether trees located on a hillslope or in the riparian zone are more effective at reducing peak flow. Results showing the underlying event conditions and how these relate to reduction in peak flow are shown. The reduction in volume of runoff is also assessed to understand catchment storage.

## 6.2 Catchment and buffer scenario parameterisation

Parameterisation for the catchment as a whole and for the buffer scenarios were determined using a combination of manual and SWAT-CUP calibration methods (See Sections 4.5 and 4.6). Catchment scale parameter changes for hourly calibration are outlined in Table 6.1 whereas a selection of important hydrological parameter values for each buffer scenario are summarised in Table 6.2.

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Table 6.1. Hourly model parameterisation for the catchment using manual calibration. Parameter values (for the whole catchment) are uniformly changed using the *replace* and *multiply* operators. Parameters changed using the *multiply* operator mostly have a series of values applied.

| Parameter changes at catchment scale | | | |
|---|---|---|---|
| ***Parameter*** | ***Definition*** | ***Operator*** | ***Parameter change/value*** |
| CN2.mgt | SCS runoff curve number for moisture condition. | Multiply | 1. -0.191833<br>2. Values >50 multiply by 0.65<br>3. 1.332 |
| SOL_AWC.sol (mm/mm) | Available water capacity of the soil layer. | Multiply | 1. 0.045<br>2. 2.75<br>3. 1.5 |
| SOL_K.sol (mm/hr) | Saturated hydraulic conductivity. | Multiply | 1. 0.461333<br>2. 1.75<br>3. 3.747978 |
| OV_N.hru | Manning's "n" value for overland flow. | Replace | Values replaced as per allocation to land use type. See Appendix 8<br>Grass Buffer = 0.14<br>Tree Buffer = 0.25 |
| GW_DELAY.gw (days) | Groundwater delay. | Replace | 20 |
| ALPHA_BF.gw (days) | Baseflow alpha factor. | Replace | 0.5 |
| GWQMN.gw (mm) | Threshold depth of water in the shallow aquifer required for return flow to occur. | Replace | 600 |
| GW_REVAP.gw | Groundwater "revap" coefficient. | Replace | 0.05 |
| REVAPMN.gw (mm) | Threshold depth of water in the shallow aquifer for "revap" to occur. | Replace | 300 |
| ESCO.hru | Soil evaporation compensation factor. | Replace | 0.25 |
| EPCO.hru | Plant uptake compensation factor. | Replace | 0.25 |
| CH_N2.rte | Manning's "n" value for the main channel. | Replace | 0.225 |
| CH_K2.rte (mm.hr) | Effective hydraulic conductivity in main channel alluvium. | Multiply | -0.382 |
| CH_N1.rte | Manning's "n" value for tributary channels. | Replace | 0.1 |
| SFTMP.bsn | Snowfall temperature. | Replace | 0 |
| SMTMP.bsn | Snow melt base temperature. | Replace | 2 |
| SMFMX.bsn | Maximum melt rate for snow during year (occurs at summer solstice). | Replace | 2 |
| SMFMN.bsn | Minimum melt rate for snow during the year (occurs at winter solstice). | Replace | 2 |
| EPCO.bsn | Plant uptake compensation factor. | Replace | 0.95 |
| SURLAG.bsn | Surface runoff lag time. | Replace | 2 |

Table 6.2 Summary of parameterisation subset for grass-based and tree-based riparian buffer strip scenarios and area of land use change for each buffer width scenario. SCS runoff curve numbers (CN2) are provided for each soil hydrological group (see Appendix 5 and 6) as CN2 values are derived based on combinations of underlying soils (of numerous types), land class and slope.

| | | **Grass Buffer** | **Tree buffer** |
|---|---|---|---|
| | **SWAT land class** | Range grasses (RNGE) | Forest Deciduous (FRSD) |
| | **Mannings n (OV_N)** | 0.14 | 0.25 |
| **CN2 for Hydrological Groups** | **A** | 49 | 45 |
| | **B** | 69 | 66 |
| | **C** | 79 | 77 |
| | **D** | 84 | 83 |
| **Land use change in catchment (67.8 km$^2$)** | **10 m Buffer** | 2% | |
| | **20 m Buffer** | 4% | |
| | **30 m Buffer** | 6% | |
| | **50 m Buffer** | 10% | |

The CN2 values outlined in Table 6.2 highlight the change in storage capacity within SWAT whereby higher CN2 values of the grass buffer equates to less storage than the lower CN2 values of tree-based buffer. Implementing land use changes like riparian buffer strips translates in SWAT hydrological terms as a change in storage capacity in the form of CN2 and soil parameter changes (e.g. SOL_AWC and SOL_K).

## 6.3 Calibration and validation

Flow peaks in the Coull hourly calibration (Figure 6.1) were overestimated with exception to one event in August 2014 where it is too low. The peaks were ultra-responsive and receded rapidly, albeit overall it showed a similar trend to the baseflow (Figure 6.1). There were too many high peaks as a result, and it is challenging to ascertain if relevant peaks coincide with observed peak timings (Figure 6.1). This would likely affect volume of runoff calculations as these ‘blocky’ shapes to the flow line will cumulatively result in lower volumes compared to observed data. The ‘blocky’ contour of the flow data shows a surprisingly high NS and $R^2$. However, in comparison to the validation year (Figure 6.2), baseflow was again too low and the ultra-responsive peaks continued, but there were less additional peaks. The simulated flows are being under predicted continuously.

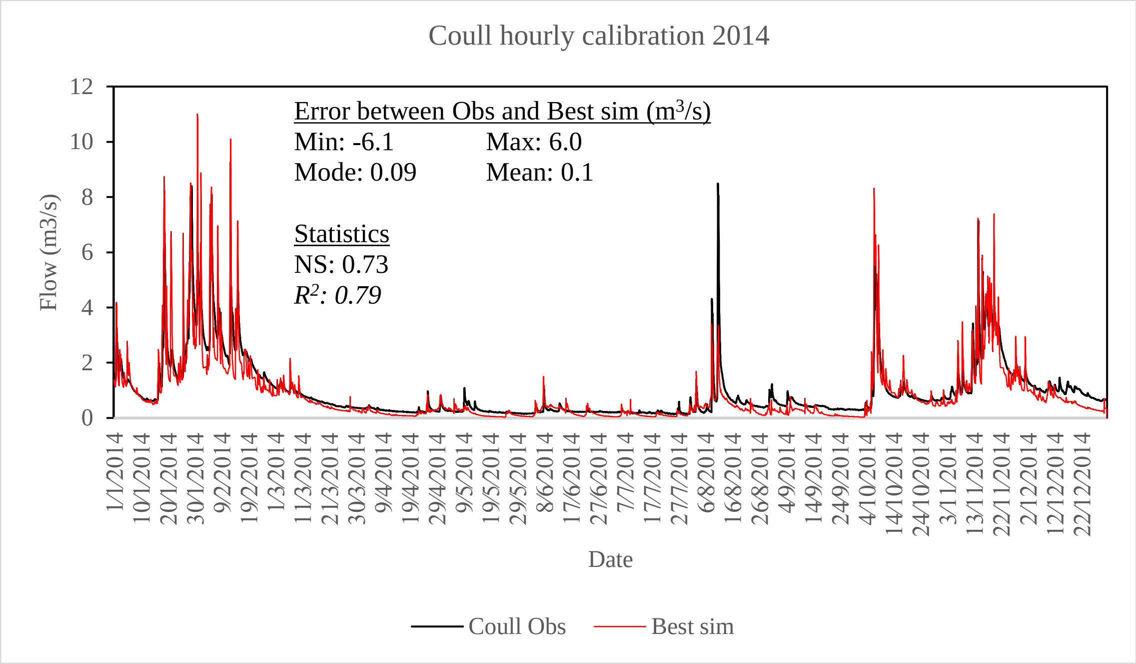



Figure 6.1. Coull hourly calibration outputs: observed vs. simulated flows.

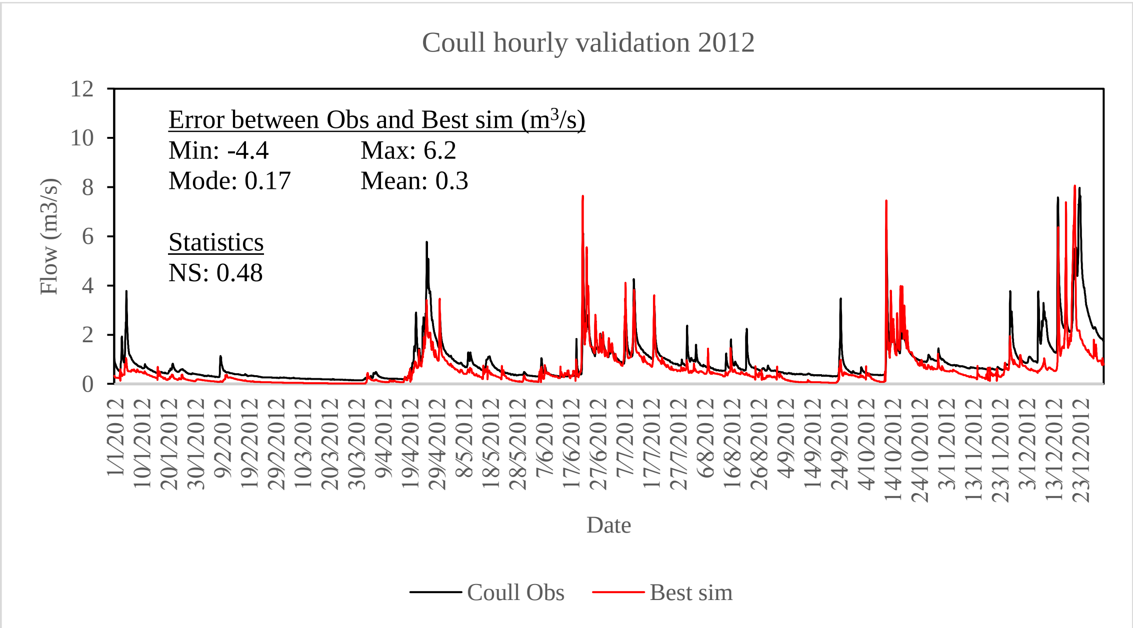



Figure 6.2. Coull hourly validation outputs: observed vs. simulated flow.

Despite extensive efforts to obtain a better goodness-of-fit through manual calibration, including consulting other authors from Boithias et al. (2017) (Boithias, 2018) (who had conducted similar SWAT hourly resolution work) to establish other methods of improvement, the outcome from hourly calibration (Figure 6.1) and validation (Figure 6.2) are the best result that could be achieved. Regardless, as stipulated above, the model was not being used to derive exact values but to provide an estimation of relative changes based on scenarios.

### *6.3.1 Field experiment scale*

The effectiveness of SWAT at smaller scale was assessed to determine whether a linkage could be made between the field experiment and the model and to understand whether SWAT could perform at such small spatial scale when calibrated at a catchment scale. Simulated outputs from the hourly model (calibrated to Coull observations) were compared at the field site (Figure 6.3). Despite changes to model parameters using extreme low and high values, limited change occurred to the simulated flows. This assessment ceased at this stage as any attempt to change the model parameters to reflect the experiment stream observations would result in catchment scale outputs not being reflective of Coull. The purpose of the modelling exercise was to assess *catchment* scale impact of riparian buffer strips.

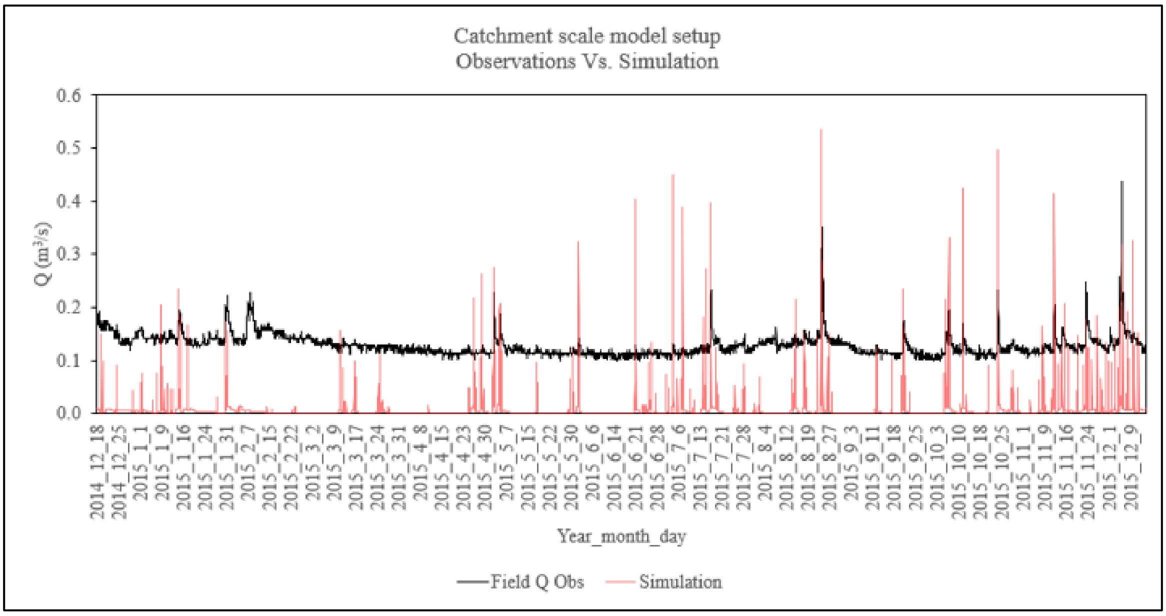



Figure 6.3. Comparison of simulated discharge at the runoff experiment site between experiment scale model setup and catchment scale model setup

## 6.4 High flow events

High flow events were determined using Coull observed discharge data and more details on how high flows were determined are provided in Chapter 4 (Section 4.4). The modelled baseline Qpk was inclusive of existing buffer strips and were compared to the Qpk of the high flow events following buffer scenario implementation. These high flow events are summarised in Table 6.3. The %↓Qpk was assessed to ascertain the effectiveness of each scenario in reducing flood risk.

Table 6.3. High flow event conditions including specification of return period/event type, depth of precipitation (pcp) and 30-day cumulative preceding antecedent precipitation index (API30).

| ***Event*** | ***Date*** | ***Event type*** | ***Pcp depth (mm)*** | ***Duration (hr)*** | ***Intensity (pcp/hr)*** | ***API30*** | ***Min Temp*** | ***Max Temp*** |
|---|---|---|---|---|---|---|---|---|
| *1* | 23/04/2000 | Q30 | 54 | 127 | 0.4 | 46.2 | 2 | 13 |
| *2* | 21/10/2002 | Q30 | 73 | 90 | 0.8 | 60.7 | 0 | 5 |
| *3* | 20/11/2002 | 1 in 2 | 68 | 56 | 1.2 | 93.2 | 7 | 9 |
| *4* | 22/11/2002 | QMED | 17 | 34 | 0.5 | 88.1 | 8 | 10 |
| *5* | 21/10/2009 | QMED | 68 | 54 | 1.3 | 20.4 | 10 | 12 |
| *6* | 1/11/2009 | 1 in 2 | 34 | 45 | 0.8 | 68.1 | 7 | 11 |
| *7* | 15/01/2010 | 1 in 2 | 37 | 39 | 1.0 | 39.7 | 2 | 5 |
| *8* | 10/8/2011 | QMED | 38 | 42 | 0.9 | 50.1 | 8 | 11 |
| *9* | 21/06/2012 | QMED | 44 | 39 | 1.1 | 33.8 | 8 | 12 |
| *10* | 11/10/2012 | 1 in 2 | 44 | 45 | 1.0 | 24.6 | -2 | 12 |
| *11* | 14/12/2012 | Q30 | 34 | 36 | 0.9 | 28.8 | 0 | 5 |
| *12* | 20/12/2012 | Q30 | 33 | 115 | 0.3 | 50.3 | 4 | 6 |
| *13* | 18/01/2014 | 1 in 2 | 38 | 47 | 0.8 | 58.9 | 0 | 7 |
| *14* | 27/01/2014 | 1 in 5 | 44 | 90 | 0.5 | 69.5 | 1 | 3 |
| *15* | 5/2/2014 | Q30 | 31 | 44 | 0.7 | 82.3 | 4 | 5 |
| *16* | 10/8/2014 | 1 in 5 | 27 | 30 | 0.9 | 47.2 | 3 | 15 |
| *17* | 7/10/2014 | QMED | 44 | 37 | 1.2 | 27.3 | 5 | 10 |
| *18* | 14/11/2014 | Q30 | 13 | 22 | 0.6 | 45.6 | 3 | 11 |
| *19* | 26/12/2015 | 1 in 2 | 33 | 33 | 1.0 | 31.0 | 0 | 4 |
| *20* | 29/12/2015 | Q10 | 45 | 33 | 1.4 | 47.7 | 7 | 10 |
| *21* | 1/1/2016 | >1 in 10 | 181 | 158 | 1.2 | 71.6 | -1 | 6 |
| | | Min | 13 | 22 | 0.3 | 20.4 | -2 | 3 |
| | | Max | 181 | 158 | 1.4 | 93.2 | 10 | 15 |

### 6.4.1 Event characteristics

The characteristics of events were essential to further explain and understand the results presented that illustrate the impact of each scenario on Ttp and Qpk. These characteristics included: the return period or percentile of the high flow event; depth of pcp; duration of the pcp event; pcp intensity (calculated by dividing total pcp depth by duration); and the 30-day cumulative antecedent precipitation index (API30). Details on how these variables were calculated are provided in Chapter 4 (Section 4.7).

As the Coull data series exists for 17 years, the accuracy of estimating return periods beyond the 1 in 10 year would be uncertain. Therefore, the 1 in 10 year event is estimated to be a 1 in 32 year event but will remain represented as a >1 in 10 year event (where the flow is equal to or greater than the flow for a 1 in 10 year event; 9.68 $m^3/s$ at Coull). Most high flow events occurred in winter (nine events) and autumn (eight events) with only three summer events and one spring event between January 2000 and January 2016.

## 6.5 Scenarios

The scenarios applied to the model consisted of changing catchment-wide riparian buffer strip widths to 10 m, 20 m, 30 m and 50 m and testing the impact when the buffers were grass-based and tree-based. An additional test was conducted to establish whether locating the deciduous trees in the riparian zone or on hillslopes would have the same or a different impact on Qpk. Details on scenario implementation are provided in Chapter 4 (Section 4.6).

### 6.5.1 Riparian buffer strip scenarios

When the width of riparian buffer strip increased as did the area of land covered by the buffer vegetation. The 10 m scenario covered 1.4 $km^2$, which equated to 2.1% of the catchment (Table 6.4). The 50 m scenario however, covered 6.9 $km^2$, equating to 10.2% of the catchment.

Table 6.4. Catchment and sub-catchment drainage area ($km^2$), and equivalent areas of land ($km^2$) covered by each scenario.

| ***Area of land ($km^2$)*** | ***Netherton*** | ***Coull*** | ***Aboyne*** | ***Catchment*** | ***% of catchment*** |
|---:|---|---|---|---|---|
| Sub-catchment drainage | 25.3 | 24.3 | 18.2 | 67.8 | |
| Cumulative drainage | 25.3 | 49.6 | 67.8 | 67.8 | |
| 10 m wide buffer | 0.5 | 0.5 | 0.4 | 1.4 | 2.1 |
| 20 m wide buffer | 1 | 1 | 0.8 | 2.8 | 4.1 |
| 30 m wide buffer | 1.5 | 1.5 | 1.1 | 4.2 | 6.2 |
| 50 m wide buffer | 2.5 | 2.5 | 1.9 | 6.9 | 10.2 |
| Hillslope trees | 3.7 | 1.9 | 1.6 | 7.1 | 10.5 |

**Land use**

The coverage areas of the different land uses replaced by each buffer scenario are outlined in Table 6.5. The dominant land uses replaced by the buffer width scenarios across the whole catchment were improved grassland, coniferous woodland and arable land, respectively (Table 6.5).

Hillslope tree catchment coverage (7.1 $km^2$) was not an identical area to the 50 m tree-based buffer scenario (6.9 $km^2$), reflected in Table 6.5. This was due to the replacement of specified areas of land parcels of heather grassland and acid grassland based on the land use input file. The time resource required to divide existing land uses and exactly match the 50 m buffer area was considered unnecessary given the small 0.2 $km^2$ difference. Land use distribution for the hillslope scenarios outlined in Section 6.5.2.

Coniferous woodland was a dominant land use removed by the buffer scenarios. Consequently, tree-based (deciduous) buffer scenarios would have replaced coniferous trees and thereby reduce the extent of catchment tree coverage that could be achieved if other land uses were replaced by trees. The removal of coniferous trees by the buffer scenarios also replaced trees with grasses during the grass-based scenarios and should be considered when discussing Qpk reduction results. With each riparian buffer strip scenario, the area of coverage and distribution of trees and grass-based land use changed across the catchment. This was captured in Table 6.6 and Table 6.7.

The coverage of trees (inclusive of scenario and existing land use trees) in each independent sub-catchment was considered to enable assessment of spatial scales of %↓Qpk. Differences in %↓Qpk may be reflected in the spatial distribution of trees in each sub-catchment. Going from upper, middle to lower catchment, the percentage tree coverage increased in each sub-catchment independently. For example, in the 10 m scenario, 18% of the upper catchment, 22% of the middle catchment and 39% of the lower catchment had tree coverage (Table 6.6). Comparing their respective tree coverages for all scenarios, the following differences were observed from Table 6.6:

- Aboyne has 20-21% more trees than Netherton;
- Coull has 4-5% more trees than Netherton;
- Aboyne has 16-19% more trees than Coull for all scenarios.

The lower catchment therefore had a larger proportion of tree-based land uses compared to the middle and upper catchment. Overall, the percentage area of the whole catchment with tree-based land uses during each buffer width scenario ranged from 25-32%, incrementally.

The main land uses removed in Netherton and Coull (for 10 m, 20 m, 30 m and 50 m width scenarios) were improved grassland, arable land and coniferous woodland, more so than the other land uses (Table 6.5). In Aboyne however, less arable land is replaced and instead, rough low productivity grassland became a more dominant land use replaced by the buffer width scenarios (Table 6.5). The dominant land uses replaced by the buffer width scenarios across the whole catchment were improved grassland, coniferous woodland and arable land, respectively (Table 6.5).

Runoff curve numbers (CN2) are determined by the combination of land use, soil properties and slope. These combinations change as tree and grass-based scenarios are implemented, resulting in altered catchment average CN2 values. CN2 values can change the available storage capacity in modelled catchments. The average catchment CN2 values for the tree-based buffer scenarios are shown to decrease incrementally for the 10 m, 20 m and 30 m buffer scenarios (Table 6.6), which increases catchment storage. However, for the 50 m buffer scenario, the average CN2 value rises to 51.42, further reducing storage. The hillslope tree scenario has the highest CN2 value (50.87; Table 6.6), which is the lowest catchment storage capacity out of all scenarios.

Table 6.5. Percentage area (km$^2$) of land use types removed by riparian buffer strip scenario implementation in each sub-catchment and at whole catchment scale. Red indicates the highest, amber the second highest and green the third highest values for the sub-catchment and scenario (e.g. for Netherton 10 m scenario). Values for each sub-catchment are not cumulative but for the independent sub-catchment area to show spatial differences in each sub-catchment.

| | *Scenario* | *Acid grassland* | *Arable* | *Coniferous* | *Deciduous* | *Heather and dwarf shrub* | *Heather grass* | *Improved grassland* | *Rough low-productivity grassland* | *Suburban* | *Urban industrial* | *Total buffer/ catchment area (km$^2$)* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Netherton | 10m | 7.9% | 22.5% | 14.7% | 7.3% | 0.2% | 1.6% | 39.6% | 5.4% | 0.1% | 0.7% | 0.5 |
| | 20m | 7.3% | 22.9% | 14.5% | 7.1% | 0.3% | 1.6% | 40.1% | 5.4% | 0.1% | 0.5% | 1.0 |
| | 30m | 7.1% | 23.2% | 14.5% | 6.9% | 0.4% | 1.6% | 40.8% | 5.5% | 0.1% | 0.0% | 1.5 |
| | 50m | 7.4% | 23.3% | 14.1% | 6.2% | 0.5% | 1.6% | 41.2% | 5.3% | 0.1% | 0.3% | 2.6 |
| | Hillslope | 57.8% | | | | | 42.2% | | | | | 3.7 |
| Coull | 10m | 3.8% | 22.4% | 9.7% | 7.1% | 0.3% | 3.2% | 47.6% | 4.2% | 1.6% | 0.0% | 0.5 |
| | 20m | 3.7% | 21.8% | 10.5% | 7.2% | 0.3% | 3.1% | 47.8% | 4.1% | 1.5% | 0.0% | 1.0 |
| | 30m | 3.5% | 22.1% | 9.7% | 7.1% | 0.3% | 3.1% | 48.6% | 4.2% | 1.5% | 0.0% | 1.4 |
| | 50m | 3.3% | 22.2% | 10.7% | 6.5% | 0.3% | 2.8% | 48.5% | 4.1% | 1.5% | 0.0% | 2.4 |
| | Hillslope | 53.0% | | | | | 47.0% | | | | | 1.9 |
| Aboyne | 10m | 0.8% | 5.6% | 29.2% | 9.4% | 0.2% | 5.3% | 27.3% | 20.7% | 0.8% | 0.8% | 0.4 |
| | 20m | 0.8% | 6.1% | 30.0% | 8.9% | 0.3% | 5.7% | 26.8% | 20.1% | 0.7% | 0.6% | 0.8 |
| | 30m | 0.8% | 6.3% | 28.9% | 8.7% | 0.4% | 5.9% | 27.7% | 20.6% | 0.6% | 0.0% | 1.1 |
| | 50m | 0.8% | 6.4% | 29.0% | 7.8% | 0.6% | 6.0% | 28.7% | 19.9% | 0.5% | 0.3% | 1.9 |
| | Hillslope | 24.2% | | | | | 75.8% | 0.0% | 0.0% | 0.0% | 0.0% | 1.6 |
| Whole catchment | 10m | 4.5% | 17.8% | 16.9% | 7.8% | 0.3% | 3.2% | 39.1% | 9.2% | 0.8% | 0.5% | 1.4 |
| | 20m | 4.2% | 17.8% | 17.4% | 7.7% | 0.3% | 3.3% | 39.1% | 9.1% | 0.8% | 0.4% | 2.8 |
| | 30m | 4.1% | 18.1% | 16.8% | 7.5% | 0.4% | 3.3% | 39.9% | 9.2% | 0.7% | 0.0% | 4.1 |
| | 50m | 4.1% | 18.2% | 17.1% | 6.8% | 0.4% | 3.2% | 40.3% | 8.9% | 0.7% | 0.2% | 6.9 |
| | Hillslope | 49.0% | | | | | 51.0% | | | | | 7.1 |
| Overall catchment km$^2$ | | 4.8 | 11.9 | 13.6 | 3.2 | 3.0 | 5.7 | 20.4 | 4.1 | 0.3 | 0.1 | 67.8 |
| Overall catchment % | | 7.1% | 17.6% | 20.1% | 4.7% | 4.4% | 8.4% | 30.1% | 6.0% | 0.5% | 0.2% | |

Table 6.6. Area ($km^2$) of tree-based land uses and tree-based riparian buffer strip. Area of deciduous trees (including those implemented in buffer scenarios) and coniferous trees within each sub-catchment and the whole catchment, during each buffer scenario. Percentage (%) of trees in each independent sub-catchment and the whole catchment during each buffer scenario are defined.

| | | ***Total area ($km^2$) of trees during each scenario*** | | | | |
|---|---|---|---|---|---|---|
| ***Site*** | ***Tree-based land use*** | ***10 m*** | ***20 m*** | ***30 m*** | ***50 m*** | ***Hillslope*** |
| Upper catchment : Netherton (25.3 $km^2$) | Deciduous & buffer | 1.5 | 1.9 | 2.4 | 3.4 | 4.6 |
| | Conifer | 3.2 | 3.1 | 3 | 2.9 | 3.3 |
| | Total area ($km^2$) of trees in sub-catchment | 4.6 | 5.0 | 5.4 | 6.2 | 7.9 |
| | % of sub-catchment area with trees | 18% | 20% | 21% | 25% | 31% |
| Middle catchment : Coull (24.3 $km^2$) | Deciduous & buffer | 2.0 | 2.4 | 2.9 | 3.8 | 3.4 |
| | Conifer | 3.4 | 3.4 | 3.3 | 3.2 | 3.5 |
| | Total area ($km^2$) of trees in sub-catchment | 5.4 | 5.8 | 6.2 | 7.1 | 6.9 |
| | % of sub-catchment area with trees | 22% | 24% | 26% | 29% | 28% |
| Lower catchment : Aboyne (18.2 $km^2$) | Deciduous & buffer | 1.1 | 1.4 | 1.8 | 2.4 | 2.3 |
| | Conifer | 6.1 | 5.9 | 5.8 | 5.7 | 6.2 |
| | Total area ($km^2$) of trees in sub-catchment | 7.1 | 7.4 | 7.6 | 8.1 | 8.5 |
| | % of sub-catchment area with trees | 39% | 41% | 42% | 45% | 47% |
| Whole catchment (67.8 $km^2$) | Deciduous & buffer | 4.5 | 5.8 | 7.1 | 9.6 | 10.4 |
| | Conifer | 12.6 | 12.4 | 12.2 | 11.8 | 12.9 |
| | Total area ($km^2$) of trees in whole catchment | 17.2 | 18.2 | 19.3 | 21.4 | 23.2 |
| | % of whole catchment area with trees | 25% | 27% | 28% | 32% | 34% |
| | Average catchment CN2 (Tree-based buffer scenarios) | 51.58 | 51.42 | 51.38 | 51.42 | 50.87 |

Table 6.7. Area (km$^2$) of grass-based land uses and grass-based riparian buffer strip. Area of grassland (including those implemented in buffer scenarios) outlined within each sub-catchment and the whole catchment, during each buffer scenario. Percentage (%) of grass-based land use in each independent sub-catchment and the whole catchment during each buffer scenario are defined.

| | | ***Total area (km$^2$) of Grass during each scenario*** | | | | |
|---|---|---|---|---|---|---|
| ***Site*** | ***Grass-based land use*** | ***10 m*** | ***20 m*** | ***30 m*** | ***50 m*** | ***Hillslope*** |
| Upper catchment: Netherton (25.3 km$^2$) | Acid grassland | 3.1 | 3.0 | 3.0 | 2.9 | 1.0 |
| | Heather grass | 2.1 | 2.1 | 2.1 | 2.1 | 0.6 |
| | Rough low-productivity grassland | 0.7 | 0.7 | 0.7 | 0.6 | 0.7 |
| | Improved | 7.6 | 7.3 | 7.1 | 6.7 | 7.8 |
| | Montane habitats | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |
| | Buffer | 0.5 | 1.0 | 1.5 | 2.5 | 3.7 |
| | Total area (km$^2$) of grassland in sub-catchment | 14.0 | 14.2 | 14.4 | 14.9 | 13.8 |
| | % of sub-catchment area with grassland | 55% | 56% | 57% | 59% | 54% |
| Middle catchment: Coull (24.3 km$^2$) | Acid grassland | 1.3 | 1.3 | 1.3 | 1.2 | 0.3 |
| | Heather grass | 1.7 | 1.6 | 1.6 | 1.6 | 0.8 |
| | Rough low-productivity grassland | 1.4 | 1.4 | 1.4 | 1.3 | 1.4 |
| | Improved | 8.3 | 8.0 | 7.8 | 7.3 | 8.5 |
| | Buffer | 0.5 | 1.0 | 1.5 | 2.5 | 1.9 |
| | Total area (km$^2$) of grassland in sub-catchment | 13.1 | 13.4 | 13.6 | 14.0 | 12.9 |
| | % of sub-catchment area with grassland | 54% | 55% | 56% | 58% | 53% |
| Lower catchment: Aboyne (18.2 km$^2$) | Acid grassland | 0.4 | 0.4 | 0.4 | 0.4 | 0.0 |
| | Heather grass | 1.9 | 1.9 | 1.9 | 1.8 | 0.7 |
| | Rough low-productivity grassland | 1.4 | 1.4 | 1.4 | 1.3 | 1.4 |
| | Improved | 4.1 | 4.0 | 3.9 | 3.7 | 4.2 |
| | Buffer | 0.4 | 0.8 | 1.1 | 1.9 | 1.6 |
| | Total area (km$^2$) of grassland in sub-catchment | 8.3 | 8.5 | 8.7 | 9.1 | 8.0 |
| | % of sub-catchment area with grassland | 45% | 47% | 48% | 50% | 44% |
| Whole catchment (67.8 km$^2$) | Acid grassland | 4.8 | 4.7 | 4.7 | 4.6 | 1.4 |
| | Heather grass | 5.7 | 5.6 | 5.6 | 5.5 | 2.1 |
| | Rough low-productivity grassland | 3.6 | 3.5 | 3.4 | 3.3 | 3.6 |
| | Improved | 20.0 | 19.4 | 18.9 | 17.8 | 20.5 |
| | Buffer | 1.4 | 2.8 | 4.2 | 6.9 | 7.1 |
| | Total area (km$^2$) of grassland in whole catchment | 35.4 | 36.0 | 36.7 | 38.0 | 34.7 |
| | % of whole catchment area with grassland | 52% | 53% | 54% | 56% | 51% |
| | Average catchment CN2 (Grass-based buffer scenarios) | 51.58 | 51.42 | 51.43 | 51.42 | 50.87 |

Likewise, understanding the grass-based land use coverage in each sub-catchment was necessary for assessing spatial scales of %↓Qpk. Where the tree-based coverage per sub-catchment increased from the upper, middle to lower sub-catchments, the grass-based scenario decreased with this incremental spatial scale. The grass-based scenarios were disproportionate to the tree-based land use coverage. The coverages highlighted in Table 6.7 illustrate the following differences between grass-based land use coverage in each sub-catchment:

- Netherton had the greatest coverage of grass-based land uses (55-59% of the sub-catchment area);
- Coull sub-catchment area had 54-58% grass-based land uses;
- Aboyne grass-based land uses covered between 8-9% less of the sub-catchment area than Netherton and Coull.

Overall, the percentage area of the whole catchment with grass-based land uses during each buffer width scenario ranged from 52-56%, incrementally. At catchment scale, there was between 24-27% more grassland (Table 6.6) than trees for each scenario (Table 6.7).

The CN2 values are the same for the tree and grass-based buffer scenarios apart from the 30 m wide scenario when the tree-based buffer has a CN value 0.05 lower than the grass-based buffer. The 30m tree-based buffer thereby has slightly more catchment storage capacity (based on CN2) compared to the grass-based buffer scenario.

**Soils**

As well as land use influencing hydrological processes, the soils in which they overlay have an important role in sub-surface and catchment hydrology. Identifying the distribution of soils in each sub-catchment was useful for later discussion on the impact of buffer scenarios on %↓Qpk at different spatial scales when each scenario was implemented.

In the upper catchment (Netherton), brown forest soils dominate (Figure 6.4) 48% sub-catchment area but the buffer scenarios overlaid mineral alluvial soils (Table 6.8) and only in wider buffer scenarios does brown forest soil become increasingly overlaid. In the middle catchment (Coull) humus-iron podzols dominate and also cover 46% whole catchment (31.2 km2), as illustrated in Table 6.8 and Figure 6.4. However, mineral alluvial soils reflect the river network and the dominant soil overlaid by the buffer scenarios at all catchment scales, despite accounting for 9% of the whole catchment. Albeit, the wider scenarios (e.g. the 30 m and 50 m) increasingly extended over noncalcareous gley (Netherton and Coull), humus iron podzol (all spatial scales), and brown forest soils (Netherton and Coull).

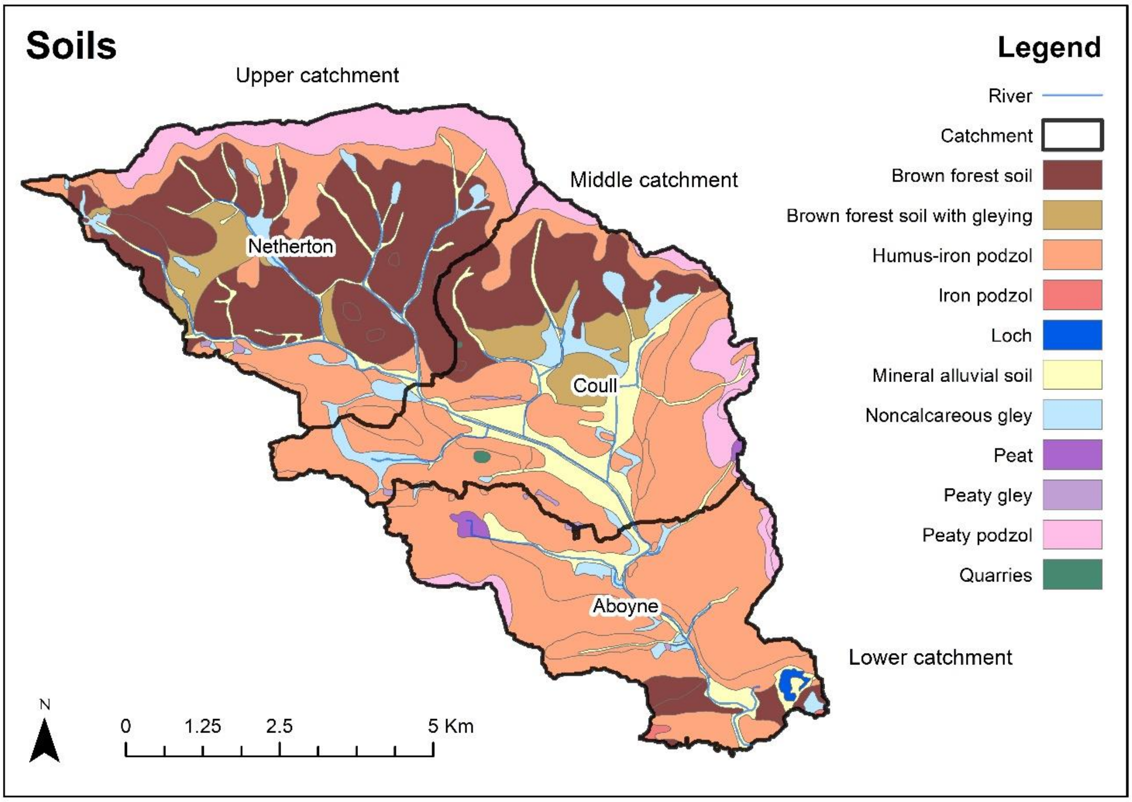



Figure 6.4. Soil distribution in Tarland catchment. Each sub-catchment (upper – Netherton; middle – Coull; and lower – Aboyne) is identified to illustrate dominant soil types at sub-catchment scale.

Table 6.8. Percentage (%) area (km$^2$) coverage of individual soil types within each sub-catchment which are overlaid by hillslope or each buffer width scenario. Coloured bars indicate visual representation of % coverage of soil for each scenario within each sub-catchment (e.g. green at Netherton is for % of soils overlaid by the 10 m scenario in the Netherton sub-catchment). Green is for 10 m scenario, yellow is for 20 m scenario, blue is for 30 m scenario, red is for 50 m scenario, aqua blue is for the hillslope scenario, and pink is for the whole catchment. Hydrological group (HyGrp) allocation for each soil type used in SWAT indicates infiltration rate status of each soil type.

| | Area (km$^2$) | Scenario | *Brown forest soil (BFS)* | *BFS with gleying* | *Humus-iron podzol* | *Iron podzol* | *Mineral alluvial soil* | *Noncalcareous gley* | *Peat* | *Peaty gley* | *Peaty podzol* | *Total buffer/ catchment area (km$^2$)* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Netherton | 25.30 | 10m | 14.91% | 0.42% | 7.17% | | 65.74% | 10.62% | | 0.73% | 0.41% | 0.5 |
| | | 20m | 18.23% | 0.85% | 8.08% | | 60.97% | 10.72% | | 0.69% | 0.46% | 1.0 |
| | | 30m | 23.23% | 1.68% | 9.57% | | 53.54% | 10.85% | | 0.62% | 0.52% | 1.5 |
| | | 50m | 32.99% | 3.86% | 12.44% | | 38.92% | 10.62% | | 0.52% | 0.65% | 2.5 |
| | | Hillslope | 28.02% | 0.91% | 30.51% | | 2.60% | 4.38% | | | 33.57% | 3.7 |
| Coull | 24.3 | 10m | 3.65% | 2.52% | 11.11% | | 73.73% | 8.78% | | | 0.22% | 0.5 |
| | | 20m | 4.87% | 3.01% | 13.16% | | 69.18% | 9.20% | 0.01% | | 0.57% | 1.0 |
| | | 30m | 6.26% | 3.78% | 16.04% | | 63.51% | 9.52% | 0.02% | | 0.88% | 1.5 |
| | | 50m | 8.37% | 5.11% | 21.17% | | 54.06% | 9.87% | 0.06% | | 1.36% | 2.5 |
| | | Hillslope | 19.72% | 0.12% | 65.51% | | 3.20% | 0.33% | | | 11.12% | 1.9 |
| Aboyne | 18.2 | 10m | 0.81% | | 26.37% | | 60.38% | 7.60% | 4.35% | 0.50% | 0.00% | 0.4 |
| | | 20m | 0.94% | | 30.07% | | 56.62% | 7.76% | 4.18% | 0.43% | 0.00% | 0.8 |
| | | 30m | 1.17% | | 34.71% | | 51.90% | 7.72% | 4.09% | 0.39% | 0.02% | 1.1 |
| | | 50m | 1.69% | | 43.76% | 0.03% | 42.85% | 7.26% | 4.00% | 0.35% | 0.07% | 1.8 |
| | | Hillslope | | | 82.79% | | 0.32% | 0.00% | | | 16.89% | 1.6 |
| Whole catchment | 67.8 | 10m | 7.01% | 1.06% | 13.81% | | 67.17% | 9.13% | 1.18% | 0.40% | 0.23% | 1.4 |
| | | 20m | 8.72% | 1.40% | 15.87% | | 62.77% | 9.37% | 1.13% | 0.37% | 0.37% | 2.8 |
| | | 30m | 11.14% | 1.99% | 18.69% | | 56.71% | 9.52% | 1.11% | 0.33% | 0.51% | 4.1 |
| | | 50m | 15.68% | 3.28% | 23.99% | 0.01% | 45.47% | 9.45% | 1.09% | 0.29% | 0.75% | 6.9 |
| | | Hillslope | 19.56% | 0.50% | 51.45% | | 2.25% | 2.33% | | | 23.91% | 7.1 |
| Overall catchment km$^2$ | | | 17.6 | 3.5 | 31.2 | 0.1 | 6.2 | 3.0 | 0.2 | 0.2 | 5.7 | 67.8 |
| Overall catchment % | | | 25.96% | 5.16% | 46.02% | 0.15% | 9.14% | 4.42% | 0.29% | 0.29% | 8.41% | |
| HyGrp | | | B | B | A | B | A | C | D | C | C | |
| HyGrp Infiltration rate status | | | Moderate | Moderate | High | Moderate | High | Slow | Very slow | Slow | Slow | |

### *6.5.2 Hillslope trees*

A comparison between implementing trees in the riparian zone or on hillslopes was conducted. The area of land covered by the 50 m buffer scenario (6.9 $km^2$) was approximately redistributed onto hillslope areas (7.1 $km^2$) where the land use was acid grassland or heather grassland (Table 6.5, page 155). Identical $km^2$ coverage was unachievable due to the size of land parcels predetermined by the land cover map. The purpose of this comparison was to understand whether the location of a similar area of trees would affect the reduction in Qpk, while additionally highlighting whether soils had a role in the degree of reduction.

**Land use**

The methodology for implementing the hillslope trees consequently resulted in heather grassland and acid grassland being the dominant land uses replaced by trees for the hillslope scenario. Nevertheless, the distribution of land uses replaced in each sub-catchment differed (Table 6.5, page 155):

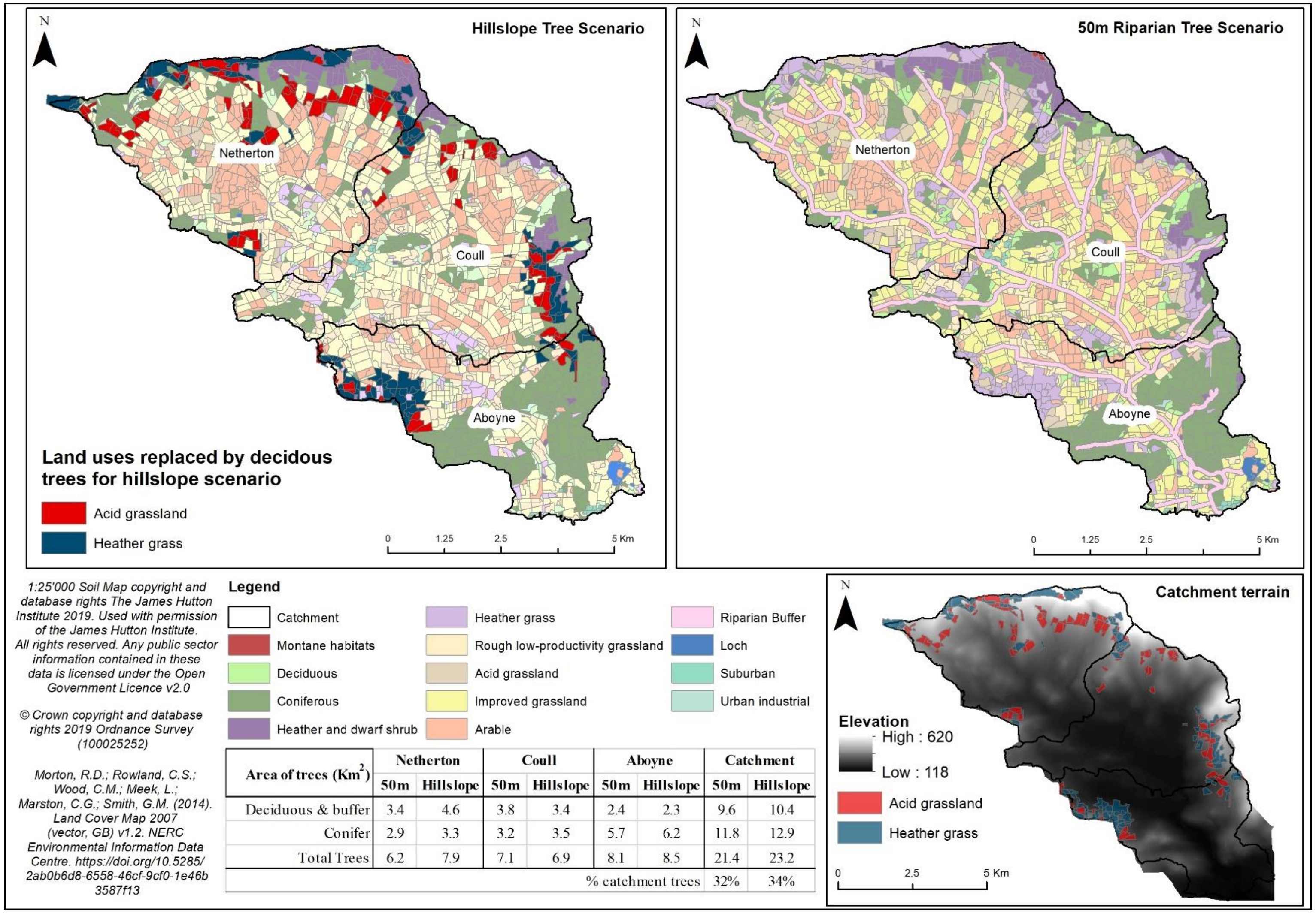
- In Netherton and Coull, the land uses replaced by hillslope trees accounted for similar percentages of heather grassland and acid grassland
- In Aboyne sub-catchment, the land uses replaced by hillslope trees accounted for 75.8% of heather grassland and 24.2% of acid grassland, which was disproportionate compared to Netherton and Coull.

In comparison, the 50 m buffer scenario removed mostly improved grassland (2.78 $km^2$), arable (1.31 $km^2$) and coniferous (1.17 $km^2$) land uses and replaced them with deciduous trees (Figure 6.5). Conversely, the hillslope tree scenario removed acid grassland (3.5 $km^2$) and heather grassland (3.64 $km^2$), and replaced these land uses with deciduous trees (Figure 6.5). A key distinction between these two scenarios was the 50 m buffer scenarios removed mostly intensively managed land uses (improved grassland and arable land), but the hillslope trees scenario replaced land uses that were not likely to be as intensively managed (acid grassland and heather grassland).

The distribution of areas covered by tree-based land uses (coniferous, deciduous and riparian buffer deciduous) are shown in Table 6.6. There was a 2% difference in the tree coverage for the whole catchment between the 50 m buffer scenario (32%) and the hillslope scenario (34%). Table 6.6 outlines the tree coverage per sub-catchment:

- Netherton: the hillslope scenario (31%) had 6% more tree coverage than the 50 m buffer scenario (25%);
- Coull: the 50 m buffer scenario (29%) had 1% more tree coverage than the hillslope scenario (28%);
- Aboyne: the hillslope scenario (47%) had 2% more tree coverage than the 50 m buffer scenario (45%).

The greatest increase in tree coverage occurred for the hillslope scenario in the upper catchment (Netherton), providing 1.2 $km^2$ more trees than the 50 m buffer scenario (Table 6.6). The deciduous trees of the 50 m buffer scenario were situated in lower elevations (Figure 6.5), which was to be expected as riparian buffer strips are situated along river networks. However, as intended, the hillslope deciduous trees were situated in the higher elevations of the catchment (Figure 6.5).




| Area of trees ($Km^2$) | Netherton | | Coull | | Aboyne | | Catchment | |
|---|---|---|---|---|---|---|---|---|
| | 50m | Hillslope | 50m | Hillslope | 50m | Hillslope | 50m | Hillslope |
| Deciduous & buffer | 3.4 | 4.6 | 3.8 | 3.4 | 2.4 | 2.3 | 9.6 | 10.4 |
| Conifer | 2.9 | 3.3 | 3.2 | 3.5 | 5.7 | 6.2 | 11.8 | 12.9 |
| Total Trees | 6.2 | 7.9 | 7.1 | 6.9 | 8.1 | 8.5 | 21.4 | 23.2 |
| % catchment trees | | | | | | | 32% | 34% |

Figure 6.5. Distribution of land uses for the 50 m buffer scenario and the hillslope scenario: elevation of hillslope tree locations and total area of trees implemented for each scenario.

**Soils**

The hillslope scenario in Figure 6.6 (left map) highlights the soil types which the hillslope deciduous trees were implemented on. Deciduous trees replaced previous land uses of acid grassland and heather grass; which overlaid predominantly humus-iron podzol (3.67 km$^2$), peaty podzol (1.71 km$^2$) and brown forest soil (1.4 km$^2$), highlighted (as percentages) in Table 6.9. The peaty podzol soils were classed in SWAT as having a slower infiltration rate (hydrological group C) than the other soils overlaid.

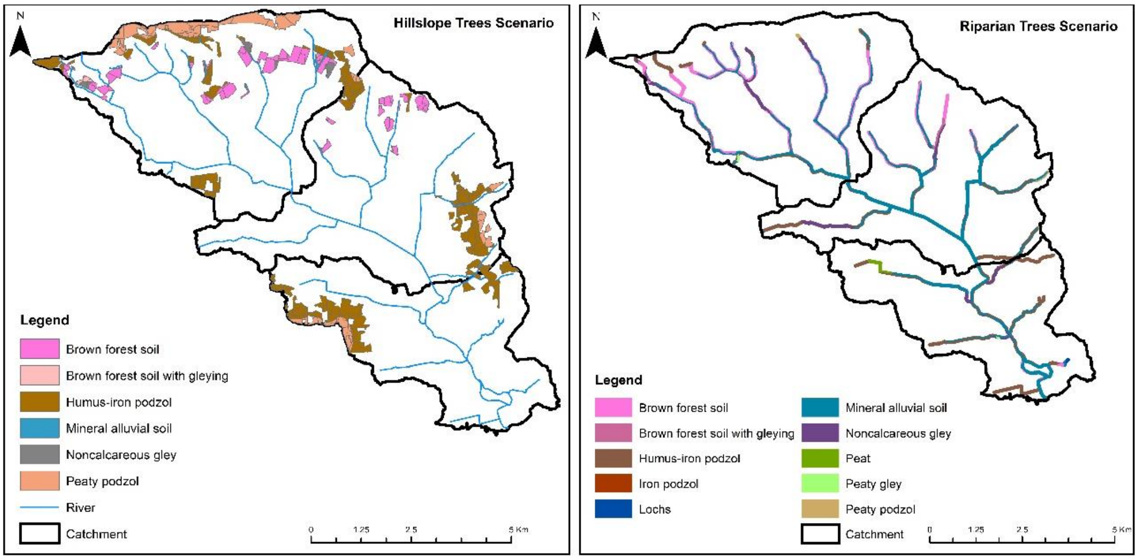



Figure 6.6. Soil overlap with hillslope tree scenario and 50 m buffer scenario.

In contrast to the hillslope scenario, the three main soils overlaid by the 50 m buffer scenario were: mineral alluvial soils (3.13 km$^2$), humus-iron podzol (1.65 km$^2$), and brown forest soils (1.07 km$^2$), also shown (as percentages) in Table 6.9. Additionally, Figure 6.6 (right map) reflects the previous summation that the mineral alluvial soils approximately traced the river network; thereby concurring the main underlying soil type of the 50 m buffer tree scenario was mineral alluvial soils.

Table 6.9. Area of soils types overlaid by riparian trees and hillslope trees

| *Soil type* | *50 m buffer (km$^2$)* | *Hillslope (km$^2$)* |
|---:|:---:|:---:|
| Brown forest soil | 1.07 | 1.40 |
| Brown forest soil with gleying | 0.22 | 0.04 |
| Humus-iron podzol | 1.65 | 3.67 |
| Iron podzol | 0.001 | - |
| Mineral alluvial soil | 3.13 | 0.16 |
| Noncalcareous gley | 0.65 | 0.17 |
| Peat | 0.08 | - |
| Peaty gley | 0.02 | - |
| Peaty podzol | 0.05 | 1.71 |
| Total area | 6.87 | 7.14 |

## 6.6 Impact on flood hazard: time to peak

For each riparian buffer width and the hillslope scenario, Ttp was assessed for each event shown in Table 6.3 to establish whether any scenario delayed the Ttp. Despite every scenario being tested at hourly timesteps for these events, there was no change in Ttp for any of the scenarios.

## 6.7 Impact on flood hazard: peak flow

The following results outline the %↓Qpk and assesses the impact at different spatial scales (upper (Netherton), middle (Coull) and lower (Aboyne) catchment). The effectiveness of varying widths of riparian buffer strip (10 m, 20 m, 30 m and 50 m), and hillslope trees on reducing Qpk are shown in conjunction with changing vegetation type (grasses and trees).

### *6.7.1 Spatial scale*

Figure 6.7 provides an overall assessment of the range of values for %↓Qpk across the three spatial scales and for all buffer width and vegetation scenarios. For all buffer width scenarios, Figure 6.7 demonstrates a greater %↓Qpk in the upper catchment (Netherton). Yet, a large range in %↓Qpk values at Netherton indicate greater uncertainty of the impact of grass and tree-based riparian buffer strips. The degree of %↓Qpk, range of values and uncertainty reduce further down the catchment at Coull and Aboyne, respectively (Figure 6.7). At the lower catchment scale (Aboyne), the %↓Qpk was reduced with less uncertainty, illustrated by a smaller range in values (albeit, the distinction between Coull and Aboyne was minimal, but Coull had greater uncertainty). An assessment of the relationship between magnitude of Qpk and %↓Qpk (see Appendix 13) further demonstrated the lower catchment scale had greater certainty in %↓Qpk. For example, %↓Qpk increased as Qpk decreased at Aboyne and had the best relationship fit compared to other spatial scales (indicating greater certainty. Full results are provided in Appendix 12 and Appendix 13.

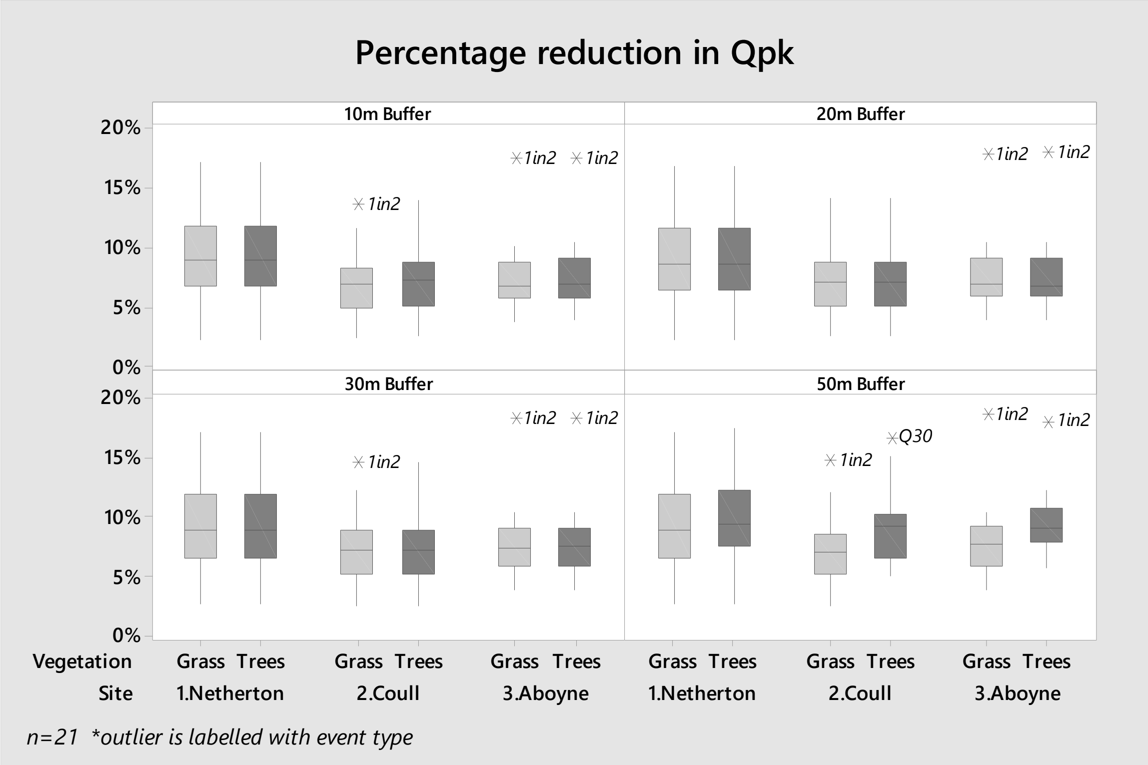



Figure 6.7.Range of percentage (%) reduction in peak flow (Qpk) for upper (Netherton), middle (Coull), and lower (Aboyne) catchment per vegetation type and per buffer width. Reduction is in comparison to baseline (with existing buffers).

### *6.7.2 Vegetation type*

The vegetation type of the 10 m, 20 m and 30 m buffer width scenarios did not show any difference in the range of %↓Qpk or the uncertainty bands (Figure 6.7). There was limited change until the 50 m scenario where a distinction between the grass and tree scenario was evident. The 50 m grass scenario illustrated a similar trend to the 10 m, 20 m and 30 m scenario (Figure 6.7). Whereas, the 50 m tree scenario exerted a distinctive change. For example, a slight shift in the range of %↓Qpk values at Netherton (Figure 6.7), which highlighted an increase in %↓Qpk for all events. The average %↓Qpk at Netherton (50 m buffer scenario) was 0.6% more for trees (9.8%), showing grasses (9.2%) to be less effective (Table 6.10). The distinction between trees and grass in the 50 m scenario at Coull and Aboyne were more pronounced (Figure 6.7) with trees (9.1% Coull, 9.5% Aboyne), having an average 1.7% greater %↓Qpk than grasses (7.4% Coull, 7.8% Aboyne) at both sites (Table 6.10).

Figure 6.8 illustrates the difference between the %↓Qpk for trees and for grasses: negative values highlight where grasses had a greater impact on reducing Qpk. At all spatial scales, the 20 m and 30 m width scenarios had minimal difference between tree reduction in Qpk and grass reduction in Qpk; the exception being event 6 at Netherton (Figure 6.8). In support of this, Table 6.10 highlights the difference between %↓Qpk for trees and grass was ≤0.4%. It also confirmed the grass scenario for event 6 at Netherton reduced peak by 1% more than trees (Table 6.10).

Excluding event 2, 10 and 11, Figure 6.8 illustrates a similar trend at the middle and lower catchment whereby the difference between %↓Qpk for trees and grasses were similar at both spatial scales. Thus, supporting the earlier statement in Section 6.7.1 regarding Figure 6.7: there was minimal distinction between Coull and Aboyne for all scenarios.

The 10 m buffer width scenario indicated a difference between grass and trees for Coull and Aboyne but the same trend was not clear in the upper catchment at Netherton (Figure 6.8). Although, Netherton illustrated a minor difference between trees and grass in the 10 m scenario for event 7 and 19.

Overall, trees were more effective at reducing Qpk, evidenced by a common trend of higher %↓Qpk across all scenarios. Despite some difference between grass and trees for the 10 m wide scenario at Coull and Aboyne, this was not incremental throughout the 20 m, 30 m and 50 m scenarios. Rather, this difference was evident only in the 10 m scenario and was more obvious for the 50 m scenario, but with limited differences in the 20 m and 30 m scenario.

There were several events where the grass vegetation was more effective at reducing Qpk. As illustrated by Figure 6.8 and Table 6.10, the following events highlighted:

- Event 7 (15 January 2010; 1 in 2)
    - Netherton 20 m grass scenario reduced Qpk by 0.1% more than trees;
    - Coull 30 m grass scenario reduced Qpk 0.1% more than trees;
    - Aboyne 10 m and 20 m grass scenarios reduced Qpk by 0.2% more than trees; and
    - Aboyne 30 m grass scenario reduced Qpk by 0.4% more than trees.
- Event 10 (11 October 2012; 1 in 2)
    - Aboyne 50 m grass scenario reduced Qpk by 0.6% more than trees.
- Event 11 (14 December 2012; Q30)
    - Coull 50 m grass scenario reduced Qpk by 0.9% more than trees.
- Event 15 (5 February 2014; Q30)
    - Netherton 20 m grass scenario reduced Qpk by 0.15% more than trees.

Table 6.10. Percentage reduction in peak flow per event, buffer width and vegetation; and difference (Diff) between grass and tree reductions.

| *Reduction in Qpk* | | | *Upper catchment - Netherton* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | *10m* | | *20m* | | *30m* | | *50m* | | *Hillslope* |
| *Event No.* | *Event type* | *Event Date* | *Grass* | *Trees* | *Grass* | *Trees* | *Grass* | *Trees* | *Grass* | *Trees* | *Trees* |
| 1 | Q30 | 23/04/00 | 17.1% | 17.1% | 16.7% | 16.7% | 17.1% | 17.1% | 17.1% | 17.5% | 16.3% |
| 2 | Q30 | 21/10/02 | 12.6% | 12.6% | 12.5% | 12.5% | 12.3% | 12.3% | 12.4% | 13.3% | 12.4% |
| 3 | 1in2 | 20/11/02 | 6.4% | 6.4% | 6.2% | 6.2% | 6.2% | 6.2% | 6.2% | 6.6% | 6.0% |
| 4 | QMED | 22/11/02 | 6.8% | 6.8% | 6.6% | 6.6% | 6.8% | 6.8% | 6.8% | 7.3% | 6.6% |
| 5 | QMED | 21/10/09 | 2.1% | 2.1% | 2.1% | 2.1% | 2.6% | 2.6% | 2.6% | 2.6% | 2.1% |
| 6 | 1in2 | 01/11/09 | 4.9% | 4.9% | 4.6% | 4.6% | 4.1% | 5.2% | 5.2% | 5.7% | 4.4% |
| 7 | 1in2 | 15/01/10 | 9.9% | 10.3% | 9.2% | 9.4% | 9.4% | 9.9% | 9.4% | 10.1% | 7.5% |
| 8 | QMED | 10/08/11 | 11.5% | 11.5% | 11.2% | 11.2% | 11.5% | 11.5% | 11.2% | 11.8% | 11.2% |
| 9 | QMED | 21/06/12 | 12.4% | 12.4% | 12.1% | 12.1% | 12.4% | 12.4% | 12.4% | 12.7% | 11.8% |
| 10 | 1in2 | 11/10/12 | 12.1% | 12.1% | 11.7% | 11.7% | 12.7% | 12.7% | 13.0% | 13.0% | 12.4% |
| 11 | Q30 | 14/12/12 | 10.2% | 10.2% | 9.9% | 9.9% | 10.5% | 10.5% | 10.8% | 11.0% | 19.8% |
| 12 | Q30 | 20/12/12 | 9.2% | 9.2% | 8.8% | 8.8% | 9.2% | 9.2% | 8.8% | 9.6% | 8.8% |
| 13 | 1in2 | 18/01/14 | 15.7% | 15.7% | 15.7% | 15.7% | 15.3% | 15.3% | 15.5% | 17.2% | 15.9% |
| 14 | 1in5 | 27/01/14 | 8.3% | 8.3% | 8.3% | 8.3% | 8.3% | 8.3% | 8.3% | 8.9% | 8.0% |
| 15 | Q30 | 05/02/14 | 5.7% | 5.7% | 5.7% | 5.7% | 5.7% | 5.7% | 5.7% | 7.5% | 6.0% |
| 16 | 1in5 | 10/08/14 | 4.5% | 4.5% | 4.5% | 4.5% | 4.5% | 4.5% | 4.5% | 4.5% | 3.7% |
| 17 | QMED | 07/10/14 | 8.3% | 8.3% | 8.0% | 8.0% | 8.5% | 8.5% | 8.5% | 8.8% | 8.3% |
| 18 | Q30 | 14/11/14 | 8.8% | 8.8% | 8.5% | 8.5% | 8.8% | 8.8% | 9.1% | 9.4% | 10.0% |
| 19 | 1in2 | 26/12/15 | 8.4% | 8.7% | 8.4% | 8.4% | 8.7% | 8.7% | 8.7% | 9.1% | 8.0% |
| 20 | Q10 | 20/12/15 | 7.5% | 7.5% | 7.2% | 7.2% | 7.7% | 7.7% | 7.7% | 7.8% | 7.5% |
| 21 | >1in10 | 02/01/16 | 9.4% | 9.4% | 9.3% | 9.3% | 9.2% | 9.2% | 9.2% | 10.8% | 9.4% |
| | | ***Average*** | 9.1% | 9.2% | 8.9% | 8.9% | 9.1% | 9.2% | **9.2%** | **9.8%** | **9.3%** |
| | | ***Min*** | 2.1% | 2.1% | 2.1% | 2.1% | 2.6% | 2.6% | 2.6% | 2.6% | 2.1% |
| | | ***Max*** | 17.1% | 17.1% | 16.7% | 16.7% | 17.1% | 17.1% | **17.1%** | **17.5%** | **19.8%** |
| | | ***Median*** | 8.8% | 8.8% | 8.5% | 8.5% | 8.8% | 8.8% | 8.8% | 9.4% | 8.3% |
| | | ***Standard Deviation*** | 3.6% | 3.6% | 3.6% | 3.6% | 3.6% | 3.6% | 3.6% | 3.7% | 4.4% |

| *Reduction in Qpk* | | | *Middle catchment - Coull* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | *10m* | | *20m* | | *30m* | | *50m* | | *Hillslope* |
| *Event No.* | *Event type* | *Event Date* | *Grass* | *Trees* | *Grass* | *Trees* | *Grass* | *Trees* | *Grass* | *Trees* | *Trees* |
| 1 | Q30 | 23/04/00 | 11.6% | 11.9% | 11.9% | 11.9% | 12.0% | 12.0% | 12.0% | 15.1% | 11.9% |
| 2 | Q30 | 21/10/02 | 11.0% | 11.7% | 11.7% | 11.7% | 12.3% | 12.3% | 11.7% | 16.6% | 12.3% |
| 3 | 1in2 | 20/11/02 | 4.8% | 4.8% | 4.8% | 4.8% | 4.8% | 4.8% | 4.8% | 6.2% | 4.8% |
| 4 | QMED | 22/11/02 | 4.7% | 5.0% | 5.0% | 5.0% | 5.1% | 5.1% | 5.0% | 7.0% | 5.2% |
| 5 | QMED | 21/10/09 | 6.5% | 6.8% | 6.8% | 6.8% | 7.0% | 7.2% | 7.0% | 7.5% | 7.0% |
| 6 | 1in2 | 01/11/09 | 3.1% | 3.6% | 3.6% | 3.6% | 3.7% | 3.9% | 3.5% | 5.6% | 4.1% |
| 7 | 1in2 | 15/01/10 | 4.6% | 4.8% | 4.7% | 4.7% | 5.2% | 5.1% | 5.2% | 5.6% | 2.9% |
| 8 | QMED | 10/08/11 | 6.9% | 7.3% | 7.3% | 7.3% | 7.7% | 7.7% | 7.2% | 9.6% | 8.4% |
| 9 | QMED | 21/06/12 | 10.2% | 10.7% | 10.6% | 10.6% | 10.6% | 10.7% | 10.5% | 11.1% | 11.0% |
| 10 | 1in2 | 11/10/12 | 13.6% | 14.0% | 14.1% | 14.1% | 14.5% | 14.5% | 14.6% | 14.6% | 16.0% |
| 11 | Q30 | 14/12/12 | 5.2% | 6.3% | 6.6% | 6.6% | 7.1% | 7.1% | 6.9% | 6.0% | 9.6% |
| 12 | Q30 | 20/12/12 | 6.8% | 7.1% | 7.1% | 7.1% | 7.1% | 7.1% | 7.1% | 9.8% | 6.9% |
| 13 | 1in2 | 18/01/14 | 7.2% | 7.6% | 7.6% | 7.6% | 7.7% | 7.8% | 7.6% | 9.4% | 8.2% |
| 14 | 1in5 | 27/01/14 | 6.8% | 7.2% | 7.1% | 7.1% | 7.2% | 7.2% | 7.1% | 9.6% | 7.4% |
| 15 | Q30 | 05/02/14 | 2.3% | 2.4% | 2.4% | 2.4% | 2.5% | 2.5% | 2.4% | 5.0% | 2.9% |
| 16 | 1in5 | 10/08/14 | 8.7% | 9.0% | 9.0% | 9.0% | 9.0% | 9.3% | 8.7% | 9.3% | 8.4% |
| 17 | QMED | 07/10/14 | 7.6% | 8.1% | 8.1% | 8.1% | 8.4% | 8.5% | 8.1% | 9.4% | 9.7% |
| 18 | Q30 | 14/11/14 | 7.8% | 8.3% | 8.3% | 8.3% | 8.6% | 8.6% | 8.3% | 10.7% | 9.7% |
| 19 | 1in2 | 26/12/15 | 4.9% | 5.5% | 5.5% | 5.5% | 5.8% | 5.8% | 5.5% | 6.7% | 6.0% |
| 20 | Q10 | 20/12/15 | 6.6% | 7.1% | 7.1% | 7.1% | 7.1% | 7.1% | 7.1% | 8.6% | 8.1% |
| 21 | >1in10 | 02/01/16 | 4.3% | 4.7% | 4.3% | 4.3% | 4.7% | 4.7% | 4.7% | 7.1% | 4.7% |
| | | ***Average*** | 6.9% | 7.3% | 7.3% | 7.3% | 7.5% | 7.6% | **7.4%** | **9.1%** | **7.9%** |
| | | ***Min*** | 2.3% | 2.4% | 2.4% | 2.4% | 2.5% | 2.5% | 2.4% | 5.0% | 2.9% |
| | | ***Max*** | 13.6% | 14.0% | 14.1% | 14.1% | 14.5% | 14.5% | **14.6%** | **16.6%** | **16.0%** |
| | | ***Median*** | 6.8% | 7.1% | 7.1% | 7.1% | 7.1% | 7.2% | 7.1% | 9.3% | 8.1% |
| | | ***Standard Deviation*** | 2.9% | 2.9% | 2.9% | 2.9% | 3.0% | 3.0% | 2.9% | 3.2% | 3.3% |

| *Reduction in Qpk* | | | *Lower catchment - Aboyne* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | *10m* | | *20m* | | *30m* | | *50m* | | *Hillslope* |
| *Event No.* | *Event type* | *Event Date* | *Grass* | *Trees* | *Grass* | *Trees* | *Grass* | *Trees* | *Grass* | *Trees* | *Trees* |
| 1 | Q30 | 23/04/00 | 9.2% | 9.4% | 9.4% | 9.4% | 9.4% | 9.4% | 9.5% | 12.2% | 9.2% |
| 2 | Q30 | 21/10/02 | 8.2% | 8.2% | 8.2% | 8.2% | 8.2% | 8.2% | 8.2% | 9.8% | 8.2% |
| 3 | 1in2 | 20/11/02 | 3.6% | 4.1% | 4.1% | 4.1% | 4.1% | 4.1% | 4.1% | 5.6% | 4.1% |
| 4 | QMED | 22/11/02 | 3.9% | 4.7% | 4.7% | 4.7% | 4.7% | 4.7% | 4.7% | 7.0% | 4.7% |
| 5 | QMED | 21/10/09 | 9.1% | 9.3% | 9.4% | 9.4% | 9.5% | 9.7% | 9.7% | 10.1% | 9.4% |
| 6 | 1in2 | 01/11/09 | 4.3% | 4.3% | 4.3% | 4.3% | 5.2% | 5.2% | 5.2% | 7.8% | 5.2% |
| 7 | 1in2 | 15/01/10 | 7.0% | 6.8% | 6.8% | 6.6% | 8.2% | 7.8% | 8.3% | 8.3% | 4.8% |
| 8 | QMED | 10/08/11 | 5.6% | 5.8% | 5.8% | 5.8% | 5.9% | 6.0% | 5.8% | 8.2% | 6.5% |
| 9 | QMED | 21/06/12 | 9.9% | 10.3% | 10.3% | 10.3% | 10.3% | 10.4% | 10.3% | 11.3% | 10.5% |
| 10 | 1in2 | 11/10/12 | 17.3% | 17.4% | 17.7% | 17.9% | 18.2% | 18.2% | 18.5% | 17.9% | 18.7% |
| 11 | Q30 | 14/12/12 | 6.6% | 6.8% | 7.2% | 7.2% | 7.0% | 7.0% | 7.7% | 7.7% | 11.6% |
| 12 | Q30 | 20/12/12 | 5.6% | 6.5% | 6.5% | 6.5% | 6.5% | 6.5% | 6.5% | 9.1% | 6.5% |
| 13 | 1in2 | 18/01/14 | 7.1% | 8.0% | 8.0% | 8.0% | 8.0% | 8.0% | 8.0% | 9.7% | 8.0% |
| 14 | 1in5 | 27/01/14 | 6.4% | 6.5% | 6.5% | 6.5% | 6.6% | 6.6% | 6.6% | 9.2% | 6.6% |
| 15 | Q30 | 05/02/14 | 3.8% | 3.8% | 3.8% | 3.8% | 3.8% | 3.8% | 3.8% | 6.8% | 3.8% |
| 16 | 1in5 | 10/08/14 | 10.0% | 10.3% | 10.3% | 10.3% | 10.0% | 10.3% | 10.3% | 10.8% | 9.8% |
| 17 | QMED | 07/10/14 | 6.6% | 6.7% | 6.7% | 6.7% | 7.4% | 7.5% | 7.6% | 9.0% | 8.1% |
| 18 | Q30 | 14/11/14 | 7.9% | 8.2% | 8.2% | 8.2% | 8.5% | 8.5% | 8.6% | 10.8% | 9.2% |
| 19 | 1in2 | 26/12/15 | 5.6% | 5.7% | 5.8% | 5.8% | 6.1% | 6.1% | 6.1% | 7.8% | 5.7% |
| 20 | Q10 | 20/12/15 | 8.4% | 8.8% | 8.8% | 8.8% | 8.8% | 8.8% | 8.8% | 11.0% | 9.3% |
| 21 | >1in10 | 02/01/16 | 5.7% | 5.7% | 5.7% | 5.7% | 5.7% | 5.7% | 5.7% | 8.5% | 5.7% |
| | | ***Average*** | 7.2% | 7.5% | 7.5% | 7.5% | 7.7% | 7.7% | **7.8%** | **9.5%** | **7.9%** |
| | | ***Min*** | 3.6% | 3.8% | 3.8% | 3.8% | 3.8% | 3.8% | 3.8% | 5.6% | 3.8% |
| | | ***Max*** | 17.3% | 17.4% | 17.7% | 17.9% | 18.2% | 18.2% | **18.5%** | **17.9%** | **18.7%** |
| | | ***Median*** | 6.6% | 6.8% | 6.8% | 6.7% | 7.4% | 7.5% | 7.7% | 9.1% | 8.0% |
| | | ***Standard Deviation*** | 3.0% | 3.0% | 3.0% | 3.1% | 3.1% | 3.1% | 3.1% | 2.5% | 3.3% |

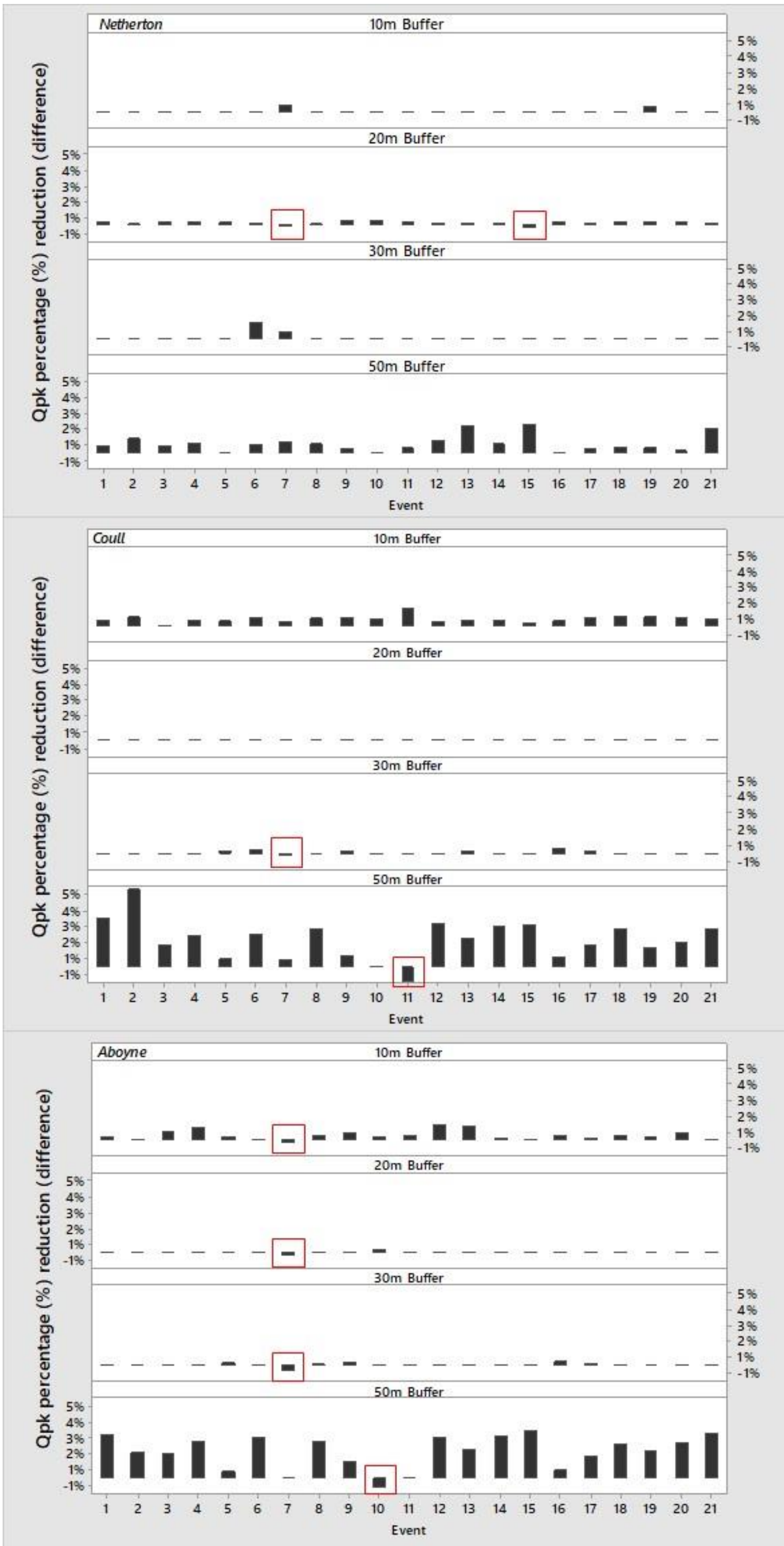



Figure 6.8. Difference between percentage (%) reduction in peak flow (Qpk) by trees and % reduction in Qpk by grasses: red squares indicate negative values, which is when grasses have a greater impact on reducing Qpk than trees.

### *6.7.3 Catchment coverage relationship to reduction in peak flow*

The area of the catchment covered by each of the riparian buffer strip width scenarios were outlined in Table 6.4 and these were compared to the average %↓Qpk for each of the scenarios (with exception to the hillslope trees). The grass-based buffer scenarios demonstrated <1 % difference in average %↓Qpk between the 10 m and 50 m width (Figure 6.9). This relationship was incremental in relation to increasing buffer width; however the rate of change in %↓Qpk slowed at the 50 m scenario. The tree-based buffer scenarios demonstrated a 2% difference in %↓Qpk in the 10 m and 50 m width buffer strips (Figure 6.9). Nevertheless, there was limited difference between the 10, 20 and 30 m scenarios and the 50 m scenario demonstrated a marked increase in %↓Qpk. Catchment coverage of buffer strip width scenarios were also compared to average catchment CN2 values (Figure 6.9). As buffer width increased, the average CN2 value reduced for grass and tree-based scenarios, which indicates an increase in catchment storage. Nevertheless, a difference was evident between the grass and tree-based buffer scenarios at 30 m width. The grass-based 30 m buffer had a higher catchment average CN2 than the tree-based 30 m buffer scenario. A higher CN2 value signals lower catchment storage capacity.

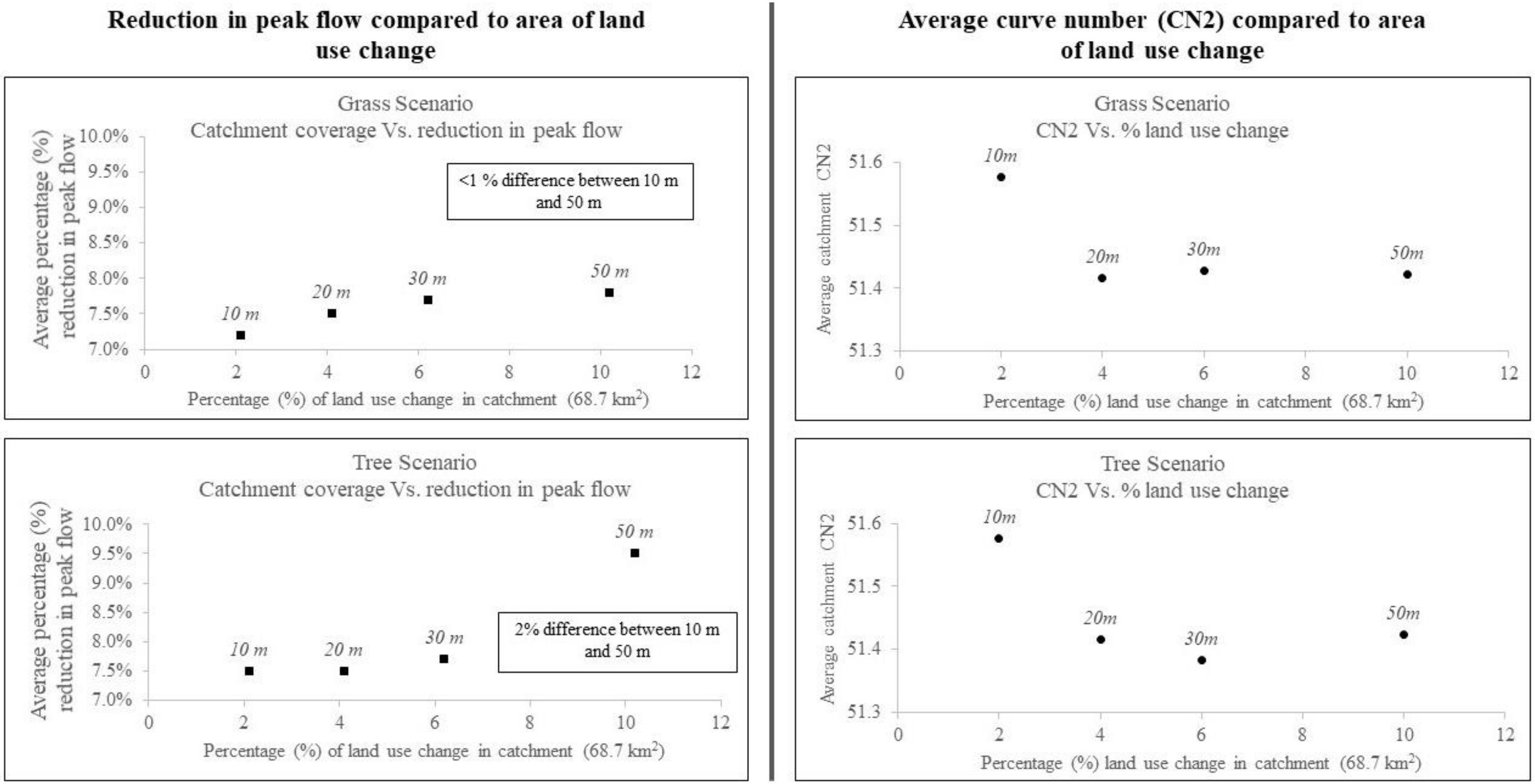



Figure 6.9. Percentage catchment coverage of each buffer width scenario with the relevant average percentage reduction in peak flow (left) for the grass (top) and tree (bottom) scenarios, and with the average catchment SCS curve number (CN2).

#### 6.7.4 *Riparian buffer strip trees vs. hillslope trees*

A clear trend (Table 6.10) indicated the hillslope tree scenario consistently had less of an impact on Qpk than the 50 m tree buffer scenario, at all spatial scales, for almost all events. However, a summary of this data, averaged over all events (Table 6.11), emphasises the average reduction of Qpk in the upper catchment was similar for hillslope and riparian trees with a 0.6% difference in effectiveness. Yet the difference in this effectiveness became more polarised further down the catchment. At Coull, the difference doubled to 1.2% and increased to 1.6% at the catchment scale at Aboyne.

Table 6.11. Difference in average percentage reduction to peak flow (%↓Qpk): 50 m tree buffer scenario vs. hillslope tree scenario

| | ***Upper catchment (Netherton)*** | ***Middle catchment (Coull)*** | ***Lower catchment (Aboyne)*** |
|---|---|---|---|
| 50 m Buffer tree scenario Average %↓Qpk | 9.8% | 9.1% | 9.5% |
| Hillslope tree scenario Average %↓Qpk | 9.3% | 7.9% | 7.9% |
| Difference in Average %↓Qpk | 0.6% | 1.2% | 1.6% |

There were three events where hillslope trees reduced Qpk more than the 50 m riparian tree buffer strips (refer to Table 6.10):

- Event 10 (1 in 2): Coull and Aboyne hillslope tree scenario reduced Qpk more than the 50 m tree buffer (1.3% and 0.8%, respectively);
- Event 11 (Q30): Netherton hillslope tree scenario reduced Qpk by 8.7% more than the 50 m tree buffer;
- Event 18 (Q30): Netherton, Coull and Aboyne all exemplified the hillslope tree scenario reduced Qpk more than the 50 m tree buffer scenario (0.6%, 3.6%, and 3.6%, respectively).

#### 6.7.5 *Peak flow reduction and event conditions*

An analysis of correlation between the %↓Qpk and event conditions (API30, pcp depth, duration and intensity) was conducted to ascertain any relationship between the two. This analysis aimed to provide an understanding of any possibility of an event condition influencing the degree of Qpk reduction. This analysis was unable to be conducted for each high flow event type (e.g QMED and 1 in 2) as the maximum sample size (n = 6) was not sufficient for statistical analysis.

All event conditions, excluding API30, had no relationship (See Appendix 14). There was a very weak negative correlation ($R^2$ between 0 and -0.19) between %↓Qpk and API30, for all buffer scenarios at Netherton (Table 6.12). However, the negative correlation strengthened in the middle catchment (Coull) to moderate ($R^2$ between -0.40 and -0.59); and only the 10 m grass scenario was not significant ($P$-value >0.05). Similarly, the strength of the correlation between %↓Qpk and API30 at (lower) catchment scale (Aboyne) strengthened further to a strong negative correlation

($R^2$ between -0.60 and -0.79) for the following scenarios: 10 m grass buffer; 30 m grass buffer; 30 m tree buffer; and the 50 m grass buffer. The remaining scenarios had a moderate negative correlation between %↓Qpk and antecedent conditions.

Table 6.12. Results of correlation between antecedent conditions (API30) and peak flow per sub-catchment.

| ***Upper catchment - Netherton*** | | | ***Middle catchment - Coull*** | | | ***Lower catchment - Aboyne*** | | |
|---|---|---|---|---|---|---|---|---|
| 10 m-Grass | $R^2$ | -0.14 | 10 m-Grass | $R^2$ | -0.42 | 10 m-Grass | $R^2$ | -0.60 |
| | *P-value* | 0.553 | | *P-value* | 0.06 | | *P-value* | 0.004 |
| 10 m-Trees | $R^2$ | -0.15 | 10 m-Trees | $R^2$ | -0.45 | 10 m-Trees | $R^2$ | -0.58 |
| | *P-value* | 0.519 | | *P-value* | 0.042 | | *P-value* | 0.006 |
| 20 m-Grass | $R^2$ | -0.13 | 20 m-Grass | $R^2$ | -0.45 | 20 m-Grass | $R^2$ | -0.59 |
| | *P-value* | 0.585 | | *P-value* | 0.039 | | *P-value* | 0.005 |
| 20 m-Trees | $R^2$ | -0.13 | 20 m-Trees | $R^2$ | -0.45 | 20 m-Trees | $R^2$ | -0.58 |
| | *P-value* | 0.577 | | *P-value* | 0.039 | | *P-value* | 0.005 |
| 30 m-Grass | $R^2$ | -0.19 | 30 m-Grass | $R^2$ | -0.47 | 30 m-Grass | $R^2$ | -0.62 |
| | *P-value* | 0.42 | | *P-value* | 0.033 | | *P-value* | 0.003 |
| 30 m-Trees | $R^2$ | -0.18 | 30 m-Trees | $R^2$ | -0.47 | 30 m-Trees | $R^2$ | -0.62 |
| | *P-value* | 0.428 | | *P-value* | 0.032 | | *P-value* | 0.003 |
| 50 m-Grass | $R^2$ | -0.18 | 50 m-Grass | $R^2$ | -0.47 | 50 m-Grass | $R^2$ | -0.63 |
| | *P-value* | 0.428 | | *P-value* | 0.032 | | *P-value* | 0.002 |
| 50 m-Trees | $R^2$ | -0.10 | 50 m-Trees | $R^2$ | -0.24 | 50 m-Trees | $R^2$ | -0.52 |
| | *P-value* | 0.668 | | *P-value* | 0.301 | | *P-value* | 0.015 |
| Hill-Trees | $R^2$ | -0.19 | Hill-Trees | $R^2$ | -0.46 | Hill-Trees | $R^2$ | -0.59 |
| | *P-value* | 0.414 | | *P-value* | 0.038 | | *P-value* | 0.005 |

For each buffer width scenario, there was limited distinction between grass and tree-based buffers in terms of correlation ($R^2$ value) between API30 and %↓Qpk, which was the case at all spatial scales Table 6.12). The only exception was the 50 m width scenario, at all spatial scales, whereby the tree scenario had weaker $R^2$ values compared to the grass scenario. The difference between the 50 m grass and 50 m tree scenario was most prominent in the middle catchment where $R^2$ changed from a significant ($P$-value <0.05) -0.47 to not significant ($P$-value >0.05) -0.24 (Table 6.12). A further observation of the API30 and %↓Qpk relationship was the similarity between the 50 m grass scenario and the 30 m tree scenario at all spatial scales (Table 6.12).

Spatially, the correlation between %↓Qpk and API30 strengthened further down the catchment, where the strongest significant ($P$-value <0.05) negative correlation was for the Aboyne 50 m grass scenario ($R^2$ = -0.63). This indicated the API30 and Qpk reduction relationship was strongest at larger spatial scale (i.e. catchment scale). Overall, the negative relationship between API30 and %↓Qpk indicated the drier the antecedent conditions related to the greater %↓Qpk, which may be due to the catchment having more storage capacity.

### *6.7.6 Catchment storage: reduction in volume of runoff*

With a reduction in Qpk for all scenarios but no evidence of change in Ttp at the hourly timestep, an assessment of the volume of runoff for the sub-catchments was explored to assess catchment storage for each scenario. The purpose of the forthcoming results was to show whether there was:

- A corresponding reduction in volume of runoff to the reduction in Qpk;
- Any of the buffer scenarios resulted a reduction in volume of runoff;
- A distinction between the reduction in volume of runoff at different spatial scales for each scenario; and to
- Examine results for an underlying event condition that may demonstrate a relationship with the reduction in volume of runoff.

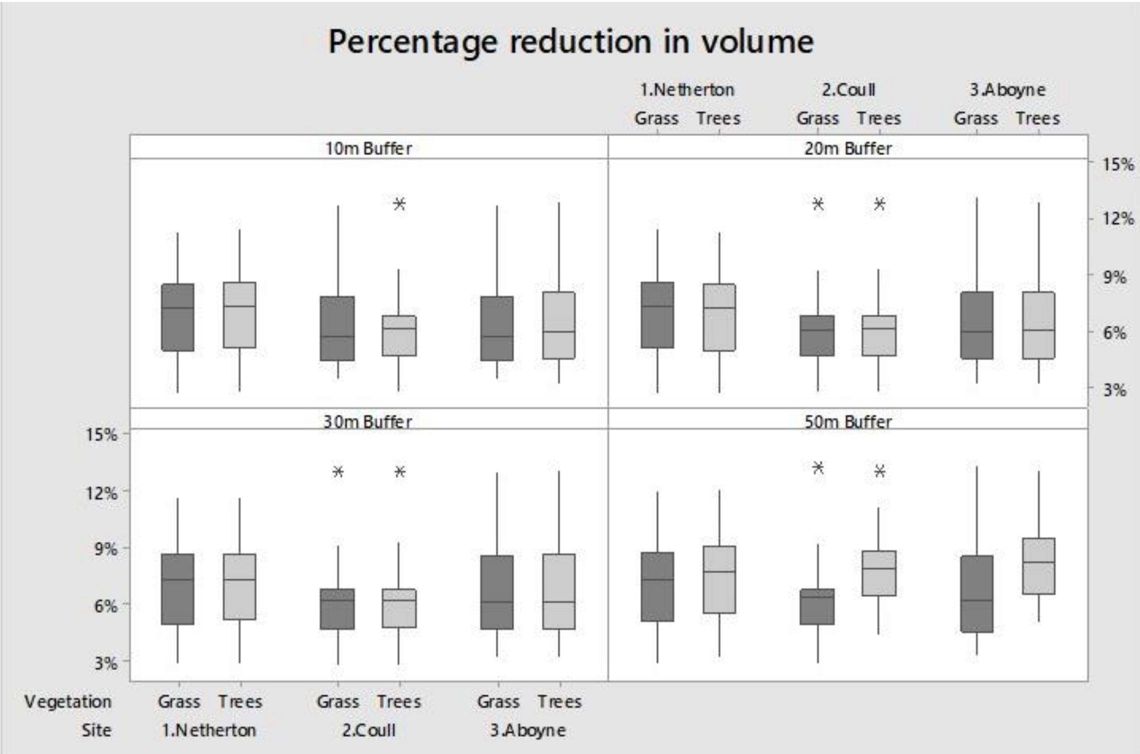



Figure 6.10. Range of percentage (%) reduction in volume of runoff for upper (Netherton), middle (Coull), and lower (Aboyne) catchment per vegetation type and per buffer width.

There was reduction in volume of runoff at all spatial scales for all buffer width and vegetation scenarios. The reduction in Qpk was therefore reflected in the reduction in volume of runoff. However, key differences between volume and Qpk in the middle catchment was the lower range of percentage change in volume compared to the upper and lower catchment; as well as the greater uncertainty for Aboyne as the 'whiskers' of the box plot (Figure 6.10) are shown to be large. Similar to Qpk (Figure 6.7), trees and grasses indicated little difference in their percentage reduction in volume of runoff (Figure 6.10) with exception to the middle catchment for the 10 m buffer width scenario and for all sub-catchments at the 50 m buffer scenario. The 50 m buffer scenario had a greater distinction between trees and grasses at Coull and Aboyne, but this distinction had greater ambiguity in the upper catchment at Netherton (Figure 6.10). In the middle and lower catchment, trees had a greater impact on the reduction of volume than grasses.

### 6.7.7 Volume reduction and event conditions

An analysis of correlation between the percentage reduction in volume of runoff and event conditions (API, pcp depth, duration and intensity) was conducted to ascertain any relationship between the two. This analysis provided an understanding of any possibility of an event condition influencing the degree of reduction in volume of runoff.

Table 6.13. Results of correlation between antecedent conditions (API30) and volume of runoff per sub-catchment.

| ***Upper catchment - Netherton*** | | | ***Middle catchment - Coull*** | | | ***Lower catchment - Aboyne*** | | |
|---|---|---|---|---|---|---|---|---|
| 10 m-Grass | $R^2$ | -0.51 | 10 m-Grass | $R^2$ | -0.68 | 10 m-Grass | $R^2$ | -0.68 |
| | *P-value* | 0.017 | | *P-value* | 0.001 | | *P-value* | 0.001 |
| 10 m-Trees | $R^2$ | -0.52 | 10 m-Trees | $R^2$ | -0.59 | 10 m-Trees | $R^2$ | -0.69 |
| | *P-value* | 0.016 | | *P-value* | 0.005 | | *P-value* | 0.001 |
| 20 m-Grass | $R^2$ | -0.51 | 20 m-Grass | $R^2$ | -0.59 | 20 m-Grass | $R^2$ | -0.70 |
| | *P-value* | 0.017 | | *P-value* | 0.005 | | *P-value* | 0.000 |
| 20 m-Trees | $R^2$ | -0.52 | 20 m-Trees | $R^2$ | -0.59 | 20 m-Trees | $R^2$ | -0.70 |
| | *P-value* | 0.017 | | *P-value* | 0.005 | | *P-value* | 0.000 |
| 30 m-Grass | $R^2$ | -0.53 | 30 m-Grass | $R^2$ | -0.61 | 30 m-Grass | $R^2$ | -0.72 |
| | *P-value* | 0.013 | | *P-value* | 0.003 | | *P-value* | 0.000 |
| 30 m-Trees | $R^2$ | -0.53 | 30 m-Trees | $R^2$ | -0.61 | 30 m-Trees | $R^2$ | -0.72 |
| | *P-value* | 0.013 | | *P-value* | 0.003 | | *P-value* | 0.000 |
| 50 m-Grass | $R^2$ | -0.53 | 50 m-Grass | $R^2$ | -0.62 | 50 m-Grass | $R^2$ | -0.73 |
| | *P-value* | 0.013 | | *P-value* | 0.003 | | *P-value* | 0.000 |
| 50 m-Trees | $R^2$ | -0.52 | 50 m-Trees | $R^2$ | -0.36 | 50 m-Trees | $R^2$ | -0.66 |
| | *P-value* | 0.016 | | *P-value* | 0.105 | | *P-value* | 0.001 |
| Hill-Trees | $R^2$ | -0.53 | Hill-Trees | $R^2$ | -0.60 | Hill-Trees | $R^2$ | -0.77 |
| | *P-value* | 0.014 | | *P-value* | 0.004 | | *P-value* | 0.000 |

All event conditions, excluding API30, showed no relationship (See Appendix 14). The antecedent conditions however, indicated moderate to strong negative correlations for all buffer scenarios and at all spatial scales (Table 6.13), which were shown to be: significant for Netherton (*P-value* ≤0.05), and highly significant at Coull (*P-value* ≤0.005) and Aboyne (*P-value* ≤0.001). There was a moderate negative correlation ($R^2$ between -0.40 and -0.59) between volume of runoff reduction and API at Netherton (Table 6.13). The strength of negative correlation increased to strong ($R^2$ between -0.60 and -0.79) at Coull except for the 10 m tree scenario, 20 m grass scenario and 20 m tree scenario where it was moderate. The 50 m tree scenario at Coull however, was weak ($R^2$ between 0 and -0.19) and not significant (*P-value* >0.05). At the catchment scale (Aboyne), all scenarios confirmed a strong negative correlation between reduction in volume of runoff and antecedent conditions; all of which were highly significant (*P-value* ≤ 0.001). Comparable to the correlation results for Qpk and API30, there was a strengthening of the correlation with increasing spatial scale. The strongest correlation occurred for the hillslope tree scenario ($R^2$ = -0.77). The moderate to strong correlations indicated drier antecedent conditions (which equates to more water holding capacity in SWAT) are closely related to a greater percentage reduction in volume of runoff. However, correlations show a relationship but do not indicate causation.

## 6.8 Chapter summary

This chapter outlined results that address RQ3. It identified twenty-one observed high-flow events at Coull that would serve as the baseline events for comparing model scenario outputs. The QMED (5 events), 1 in 2 year (6 events), Q30 (6 events) and 1 in 5 year (2 events) were analysed in more detail. The results are summarised as:

<u>Time to peak</u>

- Modelled scenarios did not change Ttp indicating any change may be at a higher resolution timestep (<1 hr).

<u>Catchment coverage and reduction in peak flow</u>

- There is a greater difference between the 10 m and 50 m scenarios when the tree-based buffer strips are implemented (2% difference. Grass-based difference <1% difference)
- With increasing area of land use change as buffer widths also increased, the CN2 generally reduced providing greater catchment storage. The single difference between the grass and tree scenarios was for the 30 m width whereby the tree-based buffer had a lower CN2 values (and therefore more storage capacity).

<u>Reduction in peak flow at different spatial scales</u>

- There was a greater %↓Qpk in the upper catchment but there was greater uncertainty of Qpk reduction at this smaller spatial scale. As spatial scale increased in the middle and lower catchment, the uncertainty in %↓Qpk reduced respectively. Additionally, as spatial scale increased, the degree of %↓Qpk reduced. This translates to the buff strips having less impact on reducing Qpk at catchment scale but more confidence quantity of Qpk reduction. Overall, this was the case for all buffer width scenarios.
- Finding all buffer scenarios reduced peak flow is a key result in this research. The 50 m tree-based buffer scenario on average had the greatest reduction in Qpk in all events. However, at each spatial scale (upper, middle and lower catchment), the difference in average %↓Qpk for each width and vegetation scenario, excluding the 50m tree buffer scenario, were similar.

Return periods and reduction in peak flow

- QMED and 1 in 2 year events at catchment scale %↓Qpk increased as Qpk decreased but not evidence at Q30 or above.
- Lower catchment had best fit for relationships based on R2, more certainty at lower magnitude events but n<20 and not reliable.
- Middle catchment less certainty for QMED but higher certainty for 1 in 2 and Q30
- Upper catchment most uncertain for 1 in 2 events
- 50 m tree buffer scenario and hillslope tree scenario demonstrated a shift in behaviour between Qpk and %↓Qpk.

Vegetation type of buffer strips and reduction in peak flow

- Only the 50 m scenario demonstrated a notable difference in the impact of trees compared to grasses on %↓Qpk. This was evident at 1 in 2 year for the upper catchment, and QMED for the middle and lower catchment.
- There was greater distinction between trees and grasses at larger spatial scales at Coull and Aboyne.
- Overall, trees more effective at %↓Qpk with consistently higher %↓Qpk in all scenarios. There were, however, anomalies identified. For example, a difference between trees and grasses at Coull and Aboyne for the 10m scenarios but this was not incremental with buffer width. Furthermore, some events resulted in grass buffer strips being more effective at reducing peak flow than trees.
    - There were some instances of grass more effective at %↓Qpk than trees

Hillslope trees vs. Riparian trees

- In the upper catchment, the difference between average %↓Qpk for hillslope and riparian trees was 0.6%. This difference increased with spatial scale (1.2% at Coull and 1.6% at Aboyne). Three out of twenty-one events did not show this same trend.

# Chapter 7 Discussion

## 7.1 Chapter introduction

The aim of this research was to establish whether riparian buffer strips are an effective NFM measure. It intended to determine their effectiveness at field and catchment scale (Figure 1.1, page 4). An ES approach was applied to simultaneously consider multiple ES likely to be affected by riparian buffer strips. Flood regulation, nutrient cycling and primary production were assessed at field scale (RQ1 and RQ2) to understand whether riparian buffer strips demonstrated NFM qualities: flood mitigation and multiple benefits (assessed as multiple ES in this study). Results from field experiments monitoring runoff attenuation (RQ1) and algae concentrations (RQ2) have been presented (Chapter 5) and are discussed in this chapter. Flood regulation was considered at catchment scale to estimate the larger spatial scale implications of riparian buffer strips on flood risk (RQ3). SWAT was utilised to estimate the impact of different riparian buffer strip scenarios on peak flows (and therefore flood risk) at catchment scale. These results are discussed in more detail in this chapter.

## 7.2 Seasonal event conditions and land management trends during runoff events

The objective of RQ1 was to ascertain the conditions when overland flow entered the riparian buffer strip, therefore engaging its ability to attenuate runoff and function as an NFM measure. This included information/analysis on event and land management conditions that occurred during events when overland flow entered the buffer strip. Event and land management conditions which coincided with greater runoff peaks, runoff volumes and contributing runoff area were assessed.

Determining conditions when overland flow was attenuated by the riparian buffer strip provides understanding of its functionality as an NFM measure. Establishing which event conditions and land management practices enhance or inhibit the riparian buffer strip's overland flow attenuation function can inform future buffer strip placement, design or management to maximise its benefits, as an NFM measure and reduce flood risk. Adjacent land management practices which inhibit overland flow attenuation in the riparian buffer strip can also be better understood.

Mann-Whitney testing identified no significance in the difference between event conditions (API30, pcp depth, duration, pcp intensity and max intensity) for infiltration and runoff events occurring. Thus, differences in rainfall event conditions between runoff and infiltration events could not adequately explain why runoff entered the buffer strip or not. This indicates other factors may be dictating whether runoff occurred in the riparian buffer strip e.g. soil conditions, hillslope hydrology or land management. However, the lack of significance may be due to a low sample number (n = 12) for conducting the test (nine runoff events and three infiltration events). An increase in sample size may change median values. The result may become significant and more statistical tests (such as multi-variate analysis or multiple regression) could be utilised to ascertain if event conditions effectively differentiate whether runoff enters the riparian buffer strip.

Conversely, the distribution of values for each event condition contrasted between infiltration events and runoff events. Results suggested higher values of pcp depth, duration and max intensity existed when overland flow entered the buffer strip.

There was no distinction between infiltration or runoff event API30 values likely due to one infiltration event later being regarded as an experimental error. The API30 was at the highest value of the experiment period during this event.

### *7.2.1 Event condition and land management trends during runoff events*

An assessment of trends in event and land management conditions provided an indication of circumstances when overland flow was able to be attenuated by entering the riparian buffer strip (a runoff event). Trends indicated thresholds for each event condition (summarised in Table 7.1) but runoff events occurred when conditions were under their thresholds and consistently coincided with higher API30 and max intensity (≥31 mm and ≥3.2 mm, respectively). For example, when pcp depth, duration and pcp intensity were below the runoff event thresholds identified (Table 7.1) a runoff event would occur when API30 or max intensity were high (≥31 mm and ≥3.2 mm, respectively).

Antecedent conditions are known to influence runoff (Pattison and Lane, 2012) whereby wetter conditions can reduce infiltration and storage capacity (Figure 7.1), resulting in saturation excess runoff generation (Horton, 1939). Intense rainfall can exceed infiltration rates and generate rapid runoff (Figure 7.1) depending on other conditions such as soil compaction and antecedent conditions (Alaoui et al., 2018). These are possible explanations as to why events with lower pcp depths continued to result in runoff entering the buffer strip due to either high antecedent conditions or intense rainfall. The event conditions were therefore identified to have trend-based thresholds. Below these thresholds, high antecedent conditions and max intensity explained why runoff occurred. It would require more research to enable statistical analysis to confirm these observations. Despite the low sample size and data being site specific, event condition threshold values (when overland flow entered the buffer strip) were identified and these indicative trends could be compared to future similar studies.

Table 7.1. Rainfall event condition trends indicative of overland flow entering the riparian buffer strip. Example values for additional thresholds are based on values obtained from Table 5.6 (page 114).

| ***Event condition*** | ***Identified trend thresholds*** | ***Additional conditions*** |
|---|---|---|
| Precipitation depth (mm) | ≥20 | - |
| | <20 | API30 is high (e.g. ≥70 mm) and/or max intensity is high (e.g. ≥3.2 mm) |
| Event duration (hours) | ≥47 | - |
| | <47 | API30 is high (e.g. ≥31 mm) and/or max intensity is high (e.g. ≥3.2 mm) |
| Maximum intensity (mm) | >1.8 | No runoff when API30 is low (e.g. ≤21 mm) |
| Antecedent conditions (API30; mm) | ≥29 | - |
| | <29 | Pcp depth (e.g. ≥23.9 mm) and max intensity (e.g. ≥3.7 mm) is high |

The influence of max intensity in defining event condition thresholds suggests more soil infiltration rate testing is required to robustly indicate whether overland flow is produced predominantly due to saturation excess or infiltration excess (and to calculate saturated hydraulic conductivity). Determining the type of overland flow can support management decisions to improve soil infiltration rates. This study found saturation excess overland flow to be dominant due to the infiltration rates in the adjacent field (29.5 mm/hr) being greater than the highest max intensity (15.5 mm/hr). Notwithstanding, this was based on one measurement, and the influence of max intensity on whether a runoff event occurred raises questions about whether overland flow was produced by means of infiltration excess or saturation excess (although not mutually exclusive). Infiltration test results are highly variable within small areas (e.g. <1 $m^2$) and caution is recommended. The interaction between API30 and max intensity would likely result in both saturation and infiltration excess overland flow when antecedent conditions were elevated, therefore reducing storage capacity in the soil (illustrated in diagram B of Figure 7.1). Any water which infiltrated the soil would have less storage capacity leading to saturation excess overland flow. Rainfall intensity could simultaneously produce infiltration excess overland flow (Figure 7.1). Understanding this in further detail would require widespread resource intensive infiltration tests across the hillslope throughout different land management categories and seasonal conditions.

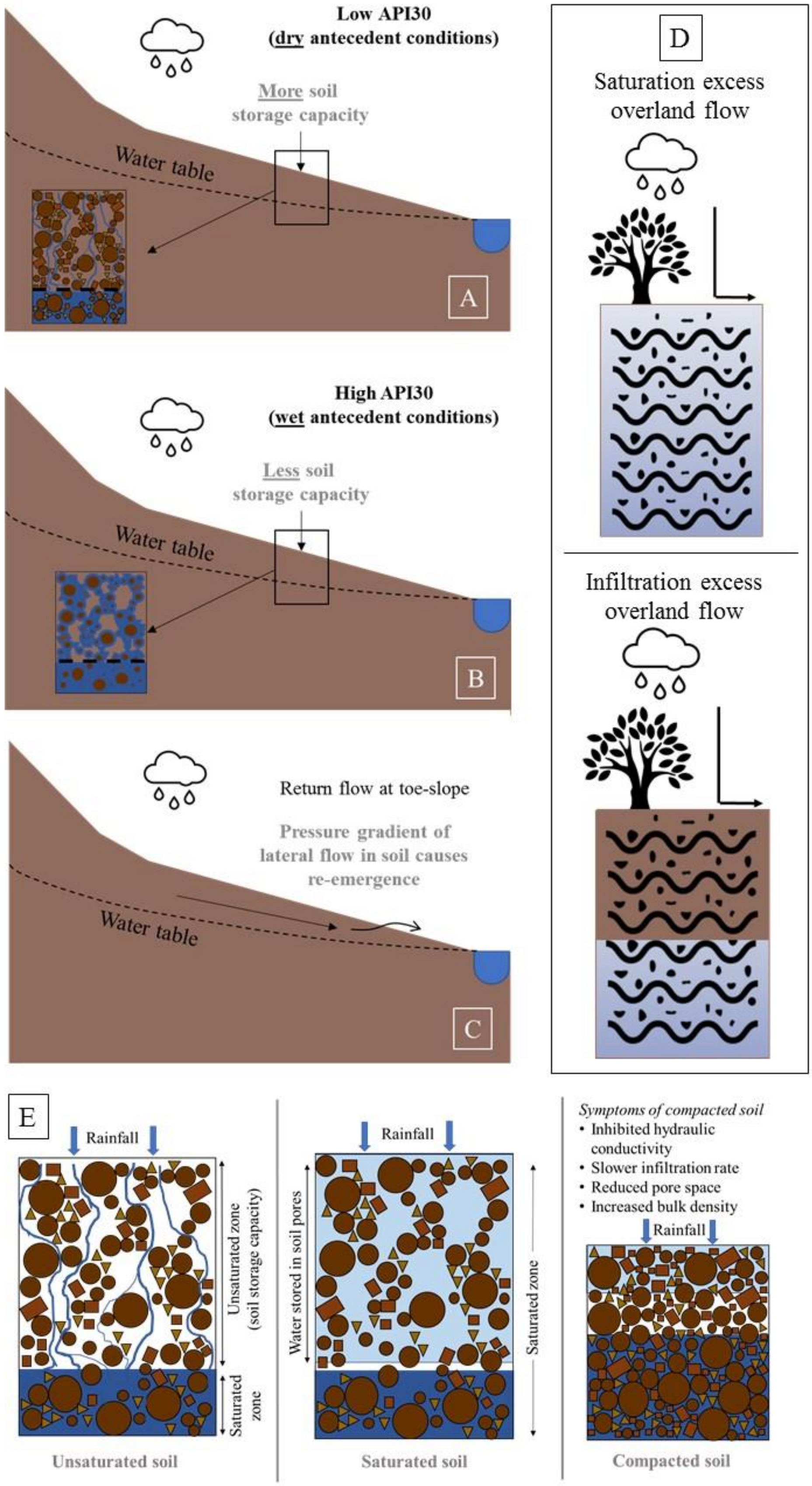



Figure 7.1 Illustration of how antecedent conditions, hillslope hydrology and soil condition affects runoff generation. Drier antecedent conditions (API30) provides greater soil storage capacity and runoff is slower to generate (A) when rainfall does not exceed infiltration rate (E); wetter API30 reduces soil storage capacity and rapid runoff is generated (B), and here assumes the water table is the same as that in diagram A; return flow at the toe-slope makes riparian buffer zones inherently wetter (C) due to seepage from lateral flows in saturated soil; overland flow can be generated by

saturation excess or infiltration excess overland flow (D); compacted (top)soil reduces pore spaces, infiltration rate and water storage capacity (E). Agricultural subsurface drainage affects water table fluctuations but are not represented here.

**Soil compaction**

Additional consideration of land management, soil conditions and the generation of overland flow is necessary to indicate the likelihood of soil compaction exacerbating the volume of runoff generated (illustrated in diagram E of Figure 7.1). A recent study of commercial farms in north eastern Scotland (Hallett et al., 2016) demonstrated the degradation of soil structure (partly by agricultural machinery and poor field drainage) enhanced runoff and presented a 'severe challenge' in understanding the consequential impact of soil degradation on flood risk. In this thesis, event condition trend thresholds became redundant when values were below the threshold for runoff to occur; and there was high API30 and max intensity. The event condition thresholds and their exceptions are possibly impacted by soil compaction from agricultural machinery. However, this would require targeted research on land management influences on soil structure and runoff generation. As illustrated by diagram A, B and E of Figure 7.1, compacted soil reduces water storage capacity (pore space availability; diagram E, Figure 7.1), which in turn reduces the antecedent storage capacity of soils (diagram A and B, Figure 7.1). The outcome being a possible faster runoff generation at lower API30 values (Bormann and Klaassen, 2008). Furthermore, compacted soil reduces infiltration rate (Chamen et al., 2003). Rapid runoff generation at lower max intensities is feasible. Soil compaction can occur in both subsoil and topsoil. However, subsoil compaction is more challenging to restore and occurs below the cultivated layer(s) of soil restricting downward water movement (Brus and van den Akker, 2018). Although soil degradation/compaction was not the focus of this study, Hallett et al. (2016) emphasised the importance of further studies to assess soil degradation, the impact on flood risk; as well as improved adoption of existing soil management practices for farmers.

**Variability in contributing area of runoff**

Each runoff event had variable contributing areas which could be a consequence of microtopography, event conditions or land management (microtopography discussion is outlined in Section 7.3). The largest contributing areas (when the runoff in the riparian buffer strip was connected to the hillslope) highlighted land management and high (wetter) API30. There were smaller contributing runoff areas when API30 was low during rainfall events with high max intensity, pcp depth and pcp intensity. As demonstrated in Figure 7.1, wetter antecedent conditions minimise the storage capacity of the soil and increase water table height, resulting in return flow at the toe-slope where buffers are usually placed.

However, land management category A1 (short crop perimeter, bare soil centre) in winter coincided with two of the highest contributing runoff areas. Greater crop coverage (A4 - short crop perimeter, swede growth centre; and A6 - tall crop) in autumn (for similarly low API30 events) corresponded to a reduced contributing runoff area. These findings suggest bare soil in the adjacent field exacerbated the hydrological connectivity in winter and wetter antecedent conditions. Consequently, this increased the contributing runoff area and runoff generation, evident by higher runoff volume in the buffer strip. O'Connell et al. (2004) suggest bare soil increases runoff and soil erosion, which is intensified by up and down slope planting of row crops. Land category A1 was when swede (row crop) were grown in the centre of the field in an up and down slope direction and the soil was bare, concurring with O'Connell et al. (2004). Agricultural practices and use of machinery increase soil compaction (Silgram et al., 2010) and create microtopographies which further exacerbates runoff generation (O'Connell et al., 2007). Silgram et al. (2010) for example, concluded runoff generation on a moderate slope of cereal crop was dominated by runoff from the tramlines with minimal runoff generated from the cereal crop area. Bare soil can be subject to surface sealing, dramatically reducing infiltration rates (Assouline, 2004). This would suggest that rain drops fragment soil aggregate into fine particles which are subsequently compacted at the soil surface by the weight of the rainfall droplets.

It was evident there was a simultaneous coincidence of land management and event conditions which resulted in a greater magnitude of runoff Qpk, runoff volume and contributing runoff area. The complex interactions between event conditions and land management can combine to create circumstances where runoff generation is exacerbated (Environment Agency, 2017a). The summer runoff event when the adjacent field had full crop cover (~1 m tall barley) was a result of the short duration (29 hr) and high intensity (max intensity 6.7 mm/hr; intensity 1.1 mm/hr) of the rainfall event. Convective storms are expected in warmer months and this event demonstrated overland flow continued to reach the riparian buffer strip despite the greater crop coverage on the hillslope. The runoff generation may be due to soil compaction from the use of agricultural machinery and intensive land management practices (O'Connell et al., 2007). For example, several studies have emphasised the role of intensive agriculture in degrading soils, which are critical to perform hydrological partitioning into infiltration and runoff, and leads to greater overland flows (Marshall et al., 2014; O'Connell et al., 2007; Wheater and Evans, 2009). The novelty in this study was the temporal monitoring of land management and cultivation changes as well as storm event conditions. Other studies tend to focus on representative plots of land management (Bronstert et al., 2002; Marshall et al., 2014) and compare their simultaneous runoff response to rainfall rather than monitor management changes in the same spatial area over time. In Fiener, Auerwald and Van Oost (2011), spatial and temporal changes in soil properties and runoff are assessed using a standardisation process of categorising timescales of land management changes in several studies to allow comparison. While this study provided only trend indications of the influence of land management, it is a challenge to implement a study which accounts for temporal changes to land management and storm conditions.

**Runoff management measures**

This study has indicated bare arable soil exacerbated runoff generation in winter during wetter antecedent conditions, as well as increased the contributing runoff area, runoff volume and runoff Qpk. This clarifies the riparian buffer strip was receiving runoff but also indicates more could be done to mitigate runoff generation from the arable field. An important observation in this study was the diversion of overland flow that consequently bypassed the riparian buffer strip. This will be discussed in Section 7.3, but should be considered in the suggested management measures to reduce runoff generation. Numerous runoff generation abatement measures could be applied at this study site:

- Hump or channel cross drains to intercept and divert concentrated overland flow paths in fields or on tracks (Quinn et al., 2008) , forcing flows into the buffer strip.
- Hedgerow to replace the riparian buffer strip fence, which would increase infiltration, and provide roughness and storage (Coates and Pattison, 2017; Holden et al., 2018) at the buffer-field interface.
- Conservation/minimum tillage practices could improve soil structure and infiltration, limiting runoff generation (Deasy et al., 2009) however, would be site dependent.
- Soil aeration to alleviate topsoil compaction.
- Subsoiling to alleviate subsoil compaction.
- Tramline management through cultivation or the use of tines (Deasy et al., 2014).

Flood risk can be reduced by minimising runoff generation from source areas (for example, hillslopes and arable land) and ensuring runoff passes into the riparian buffer strip. Ultimately, the implementation of such measures is optional for arable land managers. For example, Scottish farmers receive subsidy payments under the Single Farm Payment Scheme (SFPS) whereby they must adhere to statutory management requirements (SMR) and Good Agricultural and Environmental Conditions (GAEC) (Netregs, 2019). None of the SMRs include relevant measures that relate to reducing flood risk. The *buffer strips along water courses* GAEC (GAEC 1) restricts cultivation within two metres of a watercourse and concentrates more specifically on water quality elements (e.g. fertiliser usage) (Scottish Government, 2019a). Soil erosion mitigation is the primary aim for GAEC 4 *minimal soil cover* (Scottish Government, 2019b) and GAEC 5 *minimum land management reflecting site specific conditions to limit erosion* (Scottish Government, 2019c). However, further subsidy payments advocating land management to mitigate flood risk are available through the Agri-Environment Climate Scheme (AECS), but these are optional. Internationally, the new Farm Bill (enacted in December 2018) in the USA promotes conservation programs where farmers are paid to implement water and pollution measures such as riparian buffer strips and wetlands (USDA Natural Resources Conservation Service, 2019). Nevertheless, again this is in a voluntary capacity.

## 7.3 Microtopography influence on riparian buffer strip NFM functions

Field observations recorded for the purpose of addressing RQ1 provided evidence of overland flow being unable to enter the riparian buffer strip due to concentrated flow paths in the tramlines, parallel to the buffer strip. It was observed during two events: January 2014 and January 2016 (Figure 5.11, page 128). These tramlines created microtopography disengaging the connectivity between the hillslope and the buffer strip, providing a rapid flow path for runoff. However, field observations identified one event where an overland flow path in the adjacent field was sufficiently deep to spill into the OUTRIP V-flume. Overland flow naturally takes the path of least resistance when flowing downslope and is known to be influenced by gradient of land, slope length, vegetation and microtopography (Liu and Singh, 2004). Intensive agricultural land management can increase runoff at local and farm scale (O'Connell et al., 2007); management practices can result in microtopographies which concentrate overland flows into rills (Baiamonte and Singh, 2015). The implications of diverting concentrated flows away from the riparian buffer strip is likely increasing flood risk as runoff occurs more rapidly. It also implies the riparian buffer strip is potentially rendered inactive (at least for surface flow processes) temporarily and thereby an ineffective NFM (and potentially diffuse pollution) measure. Therefore, microtopographies require management to improve flood risk by slowing overland flow in the field, as well as ensuring connectivity between the hillslope and riparian buffer strip. Management at this fine scale may be challenging to advocate to farmers as time and resources are limited. Microtopography within the riparian buffer strip was also observed to create concentrated overland flow paths through the centre of the buffer strip.

This study was unable to obtain information on the field drain age and locations across the hillslope. The influence of field drains on intercepting near surface flows and whether flood risk is exacerbated as a result is unknown. Nevertheless, it remains a potential influencing factor in runoff generation and subsurface flow paths.

### *7.3.1 Diversion of overland flow away from the riparian buffer strip*

The influence of tramlines and microtopography concentrated flows into rills created by ploughing, which flowed parallel to the riparian buffer strip and pooled at the lower corner of the field (Figure 5.11, page 128). Several studies have determined runoff generation from wheel tracks (tramlines) is a function of reduced infiltration from compacted soil or tillage practices; providing a flow path for increased surface runoff (Dadson et al., 2017; Deasy et al., 2014, 2011; Stevens et al., 2009; Withers et al., 2006). Ephemeral flow paths emerge from the hillslope as observed by Quinn et al. (2013) in Belford catchment, create a linkage between the field, hillslope, drainage ditch and stream. Observations in this study illustrated two important findings:

i. Land management had diverted overland flow away from the buffer strip, likely increasing velocity of runoff (and in turn, sediment transport) to the stream.
ii. The diverted overland flow was pooling in the lower field corner before entering the drainage ditch at the confluence with the stream.

These findings are particularly interesting. The diversion of overland flow indicates the buffer strip is not functioning optimally by receiving overland flow to perform functions of attenuation and filtration of runoff (and pollutants/suspended sediment). Yet, the diverted flows are attenuated to a degree by pooling in the field corner. Additional management is required to disconnect the overland flow paths connecting the hillslope with the stream. For example: Deasy, Titman and Quinton (2014) suggest cultivation of the tramlines, controlled trafficking and the use of tines (large prongs or spikes). O'Connell et al. (2004) advocate timing of machinery use when soils are less saturated, as well as the adaptation of machinery tyres (use of spikes, Terra tyres, reduced tyre pressure or wider tyre width). Wilkinson et al. (2014) emphasised the benefits of disconnecting flow pathways and enhancing storage, achievable by implementing a RAF in the field corner, similar to those adopted by Wilkinson et al. (2010). This would also trap suspended sediments (SS) and therefore phosphorus (Adams et al., 2018); mitigating the limitations of the buffer strip as an NFM measure. The field corner is likely to be inherently wetter and less productive, making it a suitable location for temporary storage offering multiple benefits for water quality (Adams et al., 2018; Barber and Quinn, 2012; Verstraeten and Poesen, 1999). Depending on the size of RAF and topography, the area of land 'lost' could be minimal and the temporary nature of the RAF in less productive field corners would be more appealing to landowners.

Despite the overland flows occupying the path of least resistance and flowing parallel to the buffer strip, runoff was recorded in the OUTRIP V-flume during the high flow event in January 2014. Furthermore, a site visit enabled the discovery of overland flow being of sufficient depth to result in overspill into the buffer strip (and therefore the OUTRIP V-flume), thereby engaging the attenuation function of the buffer strip. This raises the question of conditions which result in an overland flow path depth that is adequate to allow some runoff to enter the buffer strip and be attenuated. This may be a function of event conditions or land management. For example, high intensity and high depths of rainfall may result in greater depths of overland flow, but this could be influenced by land management. The rotational nature of the land management in the adjacent field (for example, from swede to barley) could change microtopographies at the field-buffer interface following ploughing or harvesting. Moreover, a change in the microtopographies may hinder the ability of overland flow to at least partially enter the buffer strip. There is a risk of plough rills becoming deeper as they erode with each subsequent event and overland flow depths being redundant; leading to further disconnection from the field and buffer by diverting runoff until the field is next cultivated. The behaviour of overland flow paths bypassing the buffer strip may explain the lack of significant difference between event conditions for an infiltration or a runoff event (Section 7.2.1). If the overland flow paths were able to be monitored in the adjacent field, the distinction between runoff and infiltration events may have provided different results. It is clear there is an issue with buffer design and implementation which requires reconsideration to enhance their effectiveness. Work is ongoing to advocate new buffer technology and design for example, Zak et al. (2019) and Stutter et al. (2018).

Rainfall event conditions and land management influence on overland flow entering the buffer strip were explored in Section 7.2. However, the microtopography influence highlights the need for better understanding of the effect they have on riparian buffer strip NFM functionality (and in turn pollution and sediment transport). Improving hydrological connectivity between the riparian buffer strip and the hillslope could enhance riparian buffer strip ability to slow overland flow, trap more sediment and ultimately reduce flood risk. However, a range of approaches are required to enhance buffer functionality including the earlier suggestion of RAFs in field corners.

### *7.3.2 Microtopography and overland flow paths inside the riparian buffer strip*

Overland flow paths were additionally evident within the riparian buffer strip during a field visit in January 2014 (Figure 5.11, page 128). The source of this overland flow was from an access gate between the buffer strip and the field. The flows were generated from the hillslope and converged into a single flow path that meandered through the centre of the buffer strip. Previous studies (Dillaha et al., 1989; Helmers and Eisenhauer, 2006) have indicated that concentrated flows inhibit the buffer's ability to filter SS (and therefore phosphorus) and attenuate overland flow. However, it could be argued that the overland flow entering the buffer strip would otherwise have been diverted to flow in parallel with the buffer and gather additional SS. This flow would either pond in the field corner (depending on connectivity to the stream) or reach the stream with a higher load of SS.

Another factor to consider is the vegetative biomass in the buffer strip. The observed event was in winter (January 2014) when hydraulic roughness of the buffer strip vegetation would be least effective (Wagena and Easton, 2018). A study by Liu and Singh (2004) ascertained microtopography and vegetation on sloping land reduced the velocity but increase depth of overland flow. Vegetation had a greater impact than microtopography on reducing overland flow velocity (Liu and Singh, 2004). In effect, the buffer was providing a runoff attenuation function by having more vegetation (even in winter) than the adjacent field (at the time it had a short crop field perimeter with bare soil centre).

The observed overland flow paths inside the buffer strip (in winter; January 2014) may have influenced runoff event 367, which was the only event when the INRIP V-flume runoff volumes were equivalent to being 'connected to the hillslope' (Table 5.11, page 120). The larger runoff volume may have been a result of the in-buffer overland flow path being deep enough to flow into the INRIP V-flume. Notwithstanding, the INRIP runoff of event 367 remains likely to have been connected to the hillslope by way of the overland flow path inside the buffer strip.

Based on the above findings, this study tested whether these flow paths caused by microtopographies could have been identified using the 1 m resolution DTM. The derived flow paths did lead to the same area identified for the implementation of the RAF. Nevertheless, a finer resolution than 1 m is required as flow paths influenced by microtopography were not replicable in the field observations and the stream was not well represented spatially. In practice, access to DTM data of <1 m resolution may be limited, or costly to obtain. It provides also a snapshot in time of terrain conditions. At local scale, microtopographies are unlikely to be highlighted by hydrological models, justifying the necessity of field surveys. Assessment of flow paths using a 1 m resolution DTM in GIS is useful for strategic planning and high-level assessment at catchment scale, but this exercise demonstrates the requirement for ground-truthing at potential field sites before NFM measures are implemented. This approach could rapidly identify opportunities for intercepting flow paths and providing storage at catchment scale; a feasible exercise where DTM data exists. Currently, progressing work at JHI (Compagnucci et al., 2019) is exploring this concept based on this study's results. The DTM flow path assessment is being applied in various catchments, including Tarland, and is testing a rapid methodology for identifying 'quick-wins' in overland flow disconnection and storage at field corners. This work can indicate whether riparian buffer strips on slopes can be subsidised with a temporary storage pond at field corners to maximise benefits for flood risk. Farm payment schemes could utilise this information to earmark land eligible for grants to incentivise the implementation of temporary storage ponds. Adequate incentives to implement management measures to reduce runoff and maximise attenuation potential may increase the use of NFM measures and reduce flood risk.

### 7.4 Limitations of runoff field experiment

Owing to the constraints of this PhD thesis, a detailed one site investigation was conducted rather than multiple low-cost interpretations (e.g. not monitoring runoff) in order to adequately assess whether the established riparian buffer strips receive runoff generated from an agricultural hillslope. The experiment could be improved in terms of equipment errors, additional monitoring installations (e.g. rain gauge at the site) and capturing more events over time. Yet, this learning can be applied to adapt the existing site and be useful in establishing a secondary experiment site for detailed comparison. Additionally, the buffer site utilised may be similar to many buffered environments. For example, Haddaway et al. (2018), Hénault-Ethier et al. (2017) and Stehle et al. (2016). This research is a rare example of an empirically informed experiment, limitations notwithstanding, but knowledge transfer and replication are achievable through further work.

The concerns of tramlines and land management practices creating pathways, diverting and increasing velocity of overland flow have been observed in other studies (Deasy et al., 2014, 2011; Dillaha et al., 1989; Helmers and Eisenhauer, 2006; Stevens et al., 2009; Withers et al., 2006) and should remain an important finding worthy of investigation at other sites. Unlike other studies, this research recorded the changing of land management regimes, which offered insight to the types of crops and field management that coincided with observations of diversions due to tramlines, plough furrows and erosion rills. Despite the unfortunate lack of data for statistical analysis, the experiment offered valuable insight into overland flow paths and the functionality of the riparian buffer strip. There are studies that have assessed concentrated flows (Dąbrowska et al., 2018; Dillaha et al., 1989; Dosskey et al., 2002), sediment berms (Pankau et al., 2012), and microtopography (Baiamonte and Singh, 2015; Deasy et al., 2014; Silgram et al., 2010) with robust statistical testing which offer insight into potential improvements to apply to this experiment. Lobbying for consideration of these issues using the scientific evidence is required for policy change (for example, for improved tramline and wheeling management) but requires robust figures to demonstrate the benefits for reducing flood risk at all spatial scales. However, field observations are an important ground-truthing of hydrological pathways, which remain valid and underpin the direction of future work required to address these critical issues and their role in flood risk; and was achieved by this study.

Depths of runoff recorded in the V-flumes were estimations. It was necessary to apply a field calibration equation to improve runoff depth accuracy. Consequently, the contributing runoff area and volume of runoff values were also estimations. Uncertainty in the use of ultrasonic sensors (like those used in this study) have been shown to have ±7 cm error by Tekle (2014), even when temperature is compensated. On larger scale rivers, distance measurement errors of this scale are more acceptable, but highlights the uncertainty of runoff depths and volumes for this study, especially as the depth of the V-flume was 10 cm (at peak time of day in summer error was ±4 cm). Alternative approaches to recording runoff were considered for this study. For example, the use of tanks, buckets or sample bottle buried in the ground to capture runoff similar to other studies (Hénault-Ethier et al., 2017; Ocampo et al., 2006; Schulz et al., 1998; Stehle et al., 2016; Stevens et al., 2009). These studies (except Hénault-Ethier et al. 2017) were interested in sediments, pesticides and nutrients. In contrast, this study required an understanding of runoff volumes and the burial of collection vessels would not have been capable of storing large runoff volumes. Furthermore, the size of storage vessel required to be buried would have been substantial and the stony nature of the alluvial soil made this difficult to achieve. Hence, the compromise between practicality and uncertainty.

Land management observations were unable to identify the specific day when any changes occurred and could only be certain of change on the day of observation. Improvements to the design of the experiment could be achieved by using strategically placed time-lapse cameras to monitor daily changes to land management. This would enable more specific assessment of runoff events and land management changes. While this study provided only trend indications of the influence of land management, it is a challenge to implement a study which accounts for temporal changes to land management and storm conditions. Other studies (Bronstert et al., 2002; Hénault-Ethier et al., 2017; Marshall et al., 2014; Wheater et al., 2008) assess different management practices independently in manipulated isolated plots rather than over time on the same spatial area. This thesis has demonstrated the complexity of trying to capture the interaction between temporal changes in weather, cultivation practices and soil conditions.

The crops grown were identified for the adjacent field only (swede, hay, or barley). The study could be improved by ascertaining specific crop types used in the other fields and whether they (and their relevant cultivation practices) result in more runoff, or whether the riparian buffer strip is functional as an NFM measure. Installing a V-flume experiment in the riparian buffer strip at the lower corner of all the upstream fields could be used to establish whether the findings of this study apply to all the fields in the immediate surroundings regardless of crop or land management.

Catchment precipitation derived using Thiesson polygon method was used for estimating the Q5 events and uncertainty therefore surrounded the distribution, depth, duration and intensities of precipitation at the study site. Supplementary site-specific precipitation monitoring (for example, a tipping bucket rain gauge located at the experiment site) would be required to increase the certainty of event condition thresholds identified when runoff occurred. Site-specific rainfall monitoring would alleviate precipitation uncertainty for rejected events (where soil VWC, INRIP or OUTRIP runoff do not respond); confirming whether rainfall occurred at the experiment site. These suggested improvements would complement the existing findings from this research, which have provided valuable insight to the interaction between agricultural hillslope runoff and a riparian buffer strip.

API30 was derived from evaporation coefficients and catchment precipitation. It was utilised as a proxy to antecedent catchment wetness and utilised as an estimation of conditions in the absence of catchment soil moisture data. A rain gauge located at the experiment site would have negated the need for catchment precipitation calculations. To reflect the actual catchment wetness a range of further expensive monitoring would be required. For example, the use of piezometers to monitor water table heights across the hillslope and/or a gridded implementation of soil moisture probes across the adjacent field's hillslope. The quantification of subsurface and hillslope processes would be required in conjunction with considerations of land management and event conditions when runoff entered the buffer strip. A broader hydrological picture would ascertain whether riparian buffer strips should be considered an NFM measure to reduce flood risk. The constrictions of this PhD required a trade-off between variables selected for monitoring and the cost of equipment to achieve the study aim. Regardless of these limitations, it is advocated to continue to use the experiment site in its presently equipped state, or if resource permits, undertake the suggested enhancements to improve the study outputs.

## 7.5 Assessing supporting ecosystem services of riparian buffer strips using algae concentrations

This study aimed to apply an ES approach to understanding the multiple benefits of riparian buffer strips (RQ2). Algae abundance (measured as Chl-a) is widely used as an indicator of pollution and ecosystem health (Bennett et al., 2017; Environment Agency, 2016; Wu et al., 2017) and were used in this study as an indicator. Quantifying the difference between Chl-a concentrations in the buffered and non-buffered stream was achieved by calculating the EQR for each site. Statistical analysis determined whether the two sites were significantly different and the underlying causes of this were explored in terms of weather, land management and nutrients.

The ES approach adopted was the creation of a framework derived from literature which identified influences, requirements and functions of Chl-a, and indicated how these relate to specific ES (supporting, regulating, provisioning and cultural). The purpose of the framework was to assist in the discussion of Chl-a concentration results and relate these to ES (primary production and nutrient cycling) and how they may be affected.

### *7.5.1 Difference of ecological quality ratio between the buffered and non-buffered stream*

Despite the buffered and non-buffered site both being determined as having WFD-TAG (2014) *moderate* status, the EQR was higher for the buffered site (0.24) compared to the non-buffered site (0.20). This illustrated that the buffered-site was in better ecological condition (based on Chl-a concentrations) than the non-buffered site but considered within the same *moderate* status range. Nevertheless, this EQR calculation is only one aspect of the overall estimation of phytoplankton EQR. For example, overall EQR should also include the plankton trophic index (for species composition) EQR and Cyanobacteria (harmful blue-green algae) EQR, which are combined to create and overall EQR score (WFD-UKTAG, 2014). Furthermore, the WFD status of an entire waterbody is determined through a combination of factors (e.g. geomorphology, invasive species and macroinvertebrates) and an overall estimation determined (for example, this would be calculated for Tarland Burn as a whole). Irrespectively, the purpose of the EQR assessment was to use a standardised method enabling comparison between the phytoplankton ecological status of the buffered and non-buffered streams ensuring the status remains valid.

Due to the lack of standardised methodology for determining water quality status using phytoplankton in lotic systems, the EQR estimates were derived using the method employed in the UK for implementing the WFD. This methodology is optimised for lake (lentic) water bodies and is best utilised with three years worth of data. Nevertheless, it offered a technique which would standardise both the buffered and non-buffered stream Chl-a measurements, enabling comparison. Dodds and Smith (2016) recognise the lag of scientific understanding of eutrophication in rivers compared to lakes, therefore highlighting the methods and findings in lake-based studies which may inform the study of rivers. The EQR estimation requires the selection of a 'type of lake' (low alkalinity and very shallow depth <1 m) which provides a value range in which the annual geometric mean of $LOG_{10}$ Chl-a concentrations must fall between (0.3-6.0 µg/L). If the calculated geometric mean of $LOG_{10}$ Chl-a concentrations is within this range, uncertainty in the status classification is reduced (WFD-UKTAG, 2014). The buffered and non-buffered sites both had a value of 5.3 µg/L, which falls within the determined lake type range. There is ambiguity as to whether the application of the lake-based method offers an accurate representation of a stream and would require further research and analysis to conclude this; as suggested by Dodds and Smith (2016). Nonetheless, the annual geometric mean of $LOG_{10}$ Chl-a concentration and the estimation of EQR is a valid benchmark in which to compare both sites.

Possible measurement error in the Algae Torch (Kaylor et al., 2018) could affect the EQR calculation precision. This Algae Torch error may manifest when natural light conditions interfere with the fluorometer. Kaylor et al. (2018) for example, demonstrated shaded Chl-a measurements were greater than measurements taken in natural sunlight at midday, which could be affected by riparian vegetation.

### 7.5.2 *Influence of weather, land management and nutrient concentrations on algae concentrations*

Examination of trends in Chl-a concentrations compared to weather, land management and nutrient conditions obtained a greater understanding of Chl-a interactions and dynamics; especially at the buffered site where more data existed. This assessed the interaction between supporting ES (nutrient cycling and primary production) and other variables that could possibly influence conditions. At the buffered site the following conclusions were established (refer to Table 7.2):

- PCP30, API30 and number of Q5 events affect the Chl-a concentrations:
    - April, May and September 2014 had the highest peaks in Chl-a concentrations whereas; August and October 2014 had the lowest Chl-a concentrations and occurred subsequently to high Chl-a months.
    - The highest Chl-a concentration peaks (April, May and September) coincided with lower PCP30, API30 and number of Q5 events.
    - The lowest Chl-a concentrations (August and October) coincided with much higher PCP30, API30 and Q5 (wash off) events.
- Higher PCP30, API30 and number of Q5 events appear to counteract elevated nutrient levels and resulted in lower Chl-a concentrations:
    - The similarity in nutrient values between August and September ($NH_4$-N, $PO_4$-P and Total-P were slightly more elevated in September) is illustrated by Figure 5.20, page 141. Yet the Chl-a concentrations were very different (3.4 µg/L in August and 28 µg/L in September;). In August when Chl-a concentrations were much lower. This coincided with the highest PCP30, API30 and number of Q5 events.
- Land management influence on Chl-a concentrations was unclear:
    - Despite the extensive bare soil coinciding with the highest Chl-a in April, this was not consistent with other months of high Chl-a concentration (May and Sept) with tall and short crop coverage.

These conclusions suggest flow conditions are a dominant influence on algae concentrations in lotic systems and concur with Snell et al (2019, 2014). Therefore, management of algae and any depending ES (Figure 5.15, page 133) should consider runoff and storm conditions, as these affect the flow conditions.

Table 7.2. Weather, land management and nutrient conditions for months when Chlorophyll-a (Chl-a) concentration was significantly different (indicated by *) between the buffered and non-buffered site. Values highlighted in red indicate variables that may be affecting a decrease in Chl-a following a peak (buffered site only).

| ***Buffered site*** | ***Highest median Chl-a*** | | | ***Low Chl-a after being high*** | | |
|---|---|---|---|---|---|---|
| | ***Apr-14**** | ***May-14*** | ***Sep-14*** | ***Aug-14**** | ***Oct-14*** | ***Nov-14**** |
| Median Chl-a (µg/l) | 36.9 | 27.9 | 28.0 | 3.4 | 1.1 | 1.7 |
| Land management | mostly bare soil | mostly short crop | mix of tall crop and short crop | mix of tall crop and short crop | mostly short crop | mostly short crop |
| PCP30 (mm) | 19.5 | 50.7 | 60.3 | **142.2** | **106.0** | 81.0 |
| API30 (mm) | 10.8 | 25.3 | 28.5 | **58.3** | **53.0** | 42.5 |
| Mean daily temp (°C) | 5.3 | 11.7 | 13.8 | 9.3 | 6.9 | 9.6 |
| Stream temp (°C) | 6.1 | 9.3 | 10.9 | no data | 10.4 | 8.7 |
| No. Q5 events | 0 | 1 | 1 | **5** | **3** | 4 |
| No days after Chl-a sample when nutrient measurement was obtained | 2 | 7 | 2 | 2 | | 11 |
| $NH_4$-N (µg/l) | 0.024 | 0.017 | 0.045 | 0.039 | no data | 0.003 |
| $NO_3$-N (µg/l) | 4.6 | 4.2 | 5.3 | 6.3 | no data | 5.6 |
| Total-N (µg/l) | 4.6 | 4.4 | 5.6 | 6.4 | no data | 5.7 |
| DOC (µg/l) | 1.5 | 0.6 | 2.1 | 2.3 | no data | 2.5 |
| Total-P (µg/l) | 0.04 | 0.03 | 0.05 | 0.04 | no data | 0.04 |
| $PO_4$-P (µg/l) | 0.026 | 0.024 | 0.041 | 0.035 | no data | 0.037 |

| ***Non-buffered site Variable*** | ***Highest median Chl-a*** | | | | ***Low Chl-a after being high*** | |
|---|---|---|---|---|---|---|
| | ***Apr-14**** | ***May-14*** | ***Sep-14*** | ***Oct-14*** | ***Aug-14**** | ***Nov-14**** |
| Median Chl-a (µg/l) | 33.1 | 25.7 | 34.6 | 23.4 | 9.7 | 4.5 |
| PCP30 (mm) | 19.5 | 50.7 | 60.3 | 106.0 | 142.2 | 81.0 |
| API30 (mm) | 10.8 | 25.3 | 28.5 | 53.0 | 58.3 | 42.5 |
| Mean daily temp (°C) | 5.3 | 11.7 | 13.8 | 6.9 | 9.3 | 9.6 |
| Stream temp (°C) | 6.2 | 10.3 | 11.8 | 10.0 | no data | 8.5 |
| No. Q5 events | 0 | 1 | 1 | 3 | 5 | 4 |

The impact of riparian buffer strips on Chl-a concentrations was also assessed by determining whether the buffered and non-buffered site were statistically different. Mann-Whitney tests confirmed the sites differed but only statistically different for three months: April 2014 (buffered site had higher median Chl-a concentration), August 2014 and November 2014 (non-buffered site had higher median Chl-a for August and November). This suggests the riparian buffer strip does improve Chl-a conditions (in August and November 2014), which are indicative of more preferable conditions for effective nutrient cycling and primary production (supporting ES). Assessing these significantly different months in Table 7.2 alongside weather conditions does not clarify specific reasons why these months are statistically different (land management and nutrient data exist only for the buffered site). November and August for example, prompt the idea that higher

PCP30 and API30 may be a factor in the contrasting responses of Chl-a at the buffered and non-buffered sites. This could be explored by longer term monitoring of Chl-a over a range of rainfall events. However, October also had high PCP30 and API30 values (Table 7.2) and this month was not statistically significant therefore, invalidating this notion.

It is challenging to narrow specific environmental factors which affect Chl-a and nutrient relationships due to complex interactions (Figure 2.6, page 33) between land management, high flows and the spatio-temporal nature of riverine environments (Bennett et al., 2017). This study was unable to narrow any coincidental occurrence of specific land management influence on Chl-a concentrations. The lower Chl-a concentrations during higher PCP30, API30 and number of Q5 events indicate higher flows in the streams are flushing Chl-a downstream. Findings concurs with several other studies (Environment Agency, 2016; Hutchins et al., 2010; Morgan et al., 2006; Neal et al., 2006; Wu et al., 2017), indicating the coincidental reduction in Chl-a following high flows was likely fuelled by wetter antecedent conditions and heavy precipitation events; flushing sestonic algae and nutrients downstream. The consequence of Chl-a and nutrient transport along the headwaters-to-estuary continuum is the accumulation and greater concentrations downstream, which with greater residence time, can become problematic (Hutchins et al., 2010). Increased downstream accumulations of Chl-a can result in reduced oxygen and eutrophic conditions (Figure 2.6, page 33), which are ecologically destructive. Hence, the requirement for a holistic catchment-wide approach to managing nutrients. This commands effort from all land managers in an entire catchment to collectively implement their respective best management practices and cumulatively minimise nutrient transport and runoff generation.

In contrast, low flow conditions concentrate nutrients, increase stream temperatures and foster excessive algal growth which, in return, reduces oxygen and light penetration, thereby suffocating biota (Yeakley et al., 2016). This is likely when riparian shading is most important for sustaining lower temperatures and mitigating algae growth. Notably, this was evident in September when Chl-a concentrations were higher at both the buffered and non-buffered site (Table 5.15, page 134) which corresponded to lower PCP30 and API30, as well as the highest mean daily temperature and stream temperature (Table 5.16). Lower stream levels and higher ambient air temperature would enable the stream temperature to rise and concentrate nutrients ($NH_4$-N, $PO_4$-P and Total-P; Figure 5.20, page 141).

Dodds and Smith (2016) suggested weaker relationships between Chl-a and nutrients were due to shading by riparian vegetation and hydrological regimes. This would explain PCP30 and API30 counteracting the effect of nutrients in August as consequential high flows and lower temperature from shading limited Chl-a growth, despite higher nutrient concentrations. Furthermore, it may explain the lack of significant $R^2$ values for the fitted regression relationships between nutrients and Chl-a at the buffered site. Notably however, these relationships were an overview and $R^2$ should be treated with caution as there were insufficient sample sizes to conduct adequate statistical testing. The nutrient samples were also not taken on the same day of the Chl-a measurement which could explain the lack of relationship.

Nevertheless, the role of riparian shading on Chl-a concentrations was explored by Hutchins et al. (2010) and showed riparian shading had a more cost effective means of reducing Chl-a concentration than reducing nutrient levels themselves. Echoed by Burrell et al. (2014), riparian shading had a more profound effect on in-stream processes (ecosystem respiration and primary production) underpinned by algal biomass rather than percentage agricultural intensity. Warren et al. (2017) established riparian shading had a greater influence on primary production when nutrient concentrations were elevated and highlighted the research gap in understanding (spatio-temporal) variability of their interaction in stream ecosystems. Further understanding of the variability of interactions between nutrient concentration and riparian shading could determine additional cost-effective multiple benefits of riparian buffer strips in mitigating stream eutrophication (De Sosa et al., 2018b). These suggestions could have implications for this study for example, Chl-a concentrations may be better managed utilising riparian buffer strips for shading, but in conjunction with other nutrient management measures. Furthermore, it also supports the greater EQR value for the riparian buffer strip, which could be due to decreased light availability through shading from riparian vegetation.

The seasonal temperature influence is highlighted in February, March and May 2015 (Figure 5.16, page 135) demonstrating the non-buffered site Chl-a concentration to steadily increase with a greater magnitude than the buffered site. The lack of riparian shading at the non-buffered site would explain the incrementally higher Chl-a concentration compared to the buffered site.

Dale and Polasky (2007) highlight the impact of agricultural influences on ES including increased sediment loads during high flows. However, field observations of livestock poaching of the banks from August 2014 (Figure 5.22, page 143) likely had an influence on sedimentation and phosphorus (which would be attached to the soil particles). A review of riparian legislation in the UK (De Sosa et al., 2018b) indicated there is a growing realisation of the impact riparian mismanagement and livestock access to water courses is having on *good ecological* status for WFD (Terry et al., 2014). Despite the exclusion of livestock from watercourses being promoted as a best management practice, de Sosa et al. (De Sosa et al., 2018b) found no enforcement mechanisms in the UK. In August 2014, the land owner had removed part of the bank at the non-buffered site to reinstate a tile drain. Although, Chl-a concentrations were very low in August at the non-buffered site (established to be a possible consequence of elevated API30 and PCP30), Chl-a concentration in subsequent months (September and October) remained high. This could be a result of poaching, the re-sectioning of the bank and the additional flows from the tile drain, which may also be laden with nutrients.

### *7.5.3 Linkages between multiple ecosystem services*

The Chl-a ES framework (Figure 5.15, page 133) was derived from literature to aid the interpretation of localised conditions and how these may translate to catchment scale. This assessment was limited in terms of quantifying the impact on ES. However, the framework enables understanding of riparian buffer strips and their multiple benefits as an NFM measure in the context of algae and the interaction with wider ES, which could identify further areas of research.

Yeakley et al. (2016) identified the role of headwaters in ES provision using Syrbe and Walz (2012) concept of 'service provisioning areas' (SPAs). Riparian headwater's SPA role is to dilute, purify and retain nutrients and provide a water supply to lower catchment ecosystems (Yeakley et al., 2016). The upper catchment is a prime area to intercept hydrological flow paths (as the catchment is generally steeper) and store water during rainfall events to minimise the volume and velocity of runoff.

**Chl-a influences from the study sites**

The *moderate* status of the buffered and non-buffered sites indicated an imbalance of algae biomass that can have implications for ES. The buffered site demonstrated a higher EQR and thereby improved ecological condition in the stream. The influences on Chl-a identified by the ES framework translate to likely influences detected in this study:

- Land management:
    - Poaching of the banks and excavation of the bank to expose a tile drain at the non-buffered site coincided with increased Chl-a concentration in subsequent months. This could have increased nutrient loads and in combination with limited shading and higher temperatures prompted an increase in Chl-a concentrations.
    - At the buffered site, tramlines with compacted soil impeded the ability of the riparian buffer strip to receive overland flow, attenuate runoff, trap sediment and filter nutrients which were otherwise transported more directly to the stream.
    - The buffer strip was fenced off to livestock and provided shading to regulate stream temperature, as well as vegetation to intercept runoff (and sediment) and uptake nutrients (although full functionality is questioned due to the diversion of overland flow by the tramlines). The non-buffered site had (mostly) higher stream temperature and less shading.
- Weather and high flows
    - Antecedent conditions, high intensity and depths of precipitation events were shown to coincide with very low Chl-a concentrations, indicating a dilution and flushing further downstream.
    - These conditions were also associated with higher runoff volumes, which were exacerbated by bare soil in the adjacent field of the buffered site.

**Implications for Chl-a functions and ecosystem services**

These influences on Chl-a and the dynamics of how concentrations are affected may have an impact on ES. High Chl-a concentrations like those evident in April, May, September and October may have temporarily disrupted biogeochemical processes (nutrient cycling and primary production) which provide food for higher trophic levels of the food chain (Dodds, 2006; Elliott et al., 2004). Higher Chl-a concentrations are expected in spring with flow, temperature and light being the limiting influences (Carvalho et al., 2002). Greater Chl-a concentrations at the study sites will be transported downstream and therefore it depends on the cumulative conditions downstream in the River Dee as to what impact the increased phytoplankton will have. This would affect the nutrient cycling and primary production as supporting ES. For example, high Chl-a concentrations can reduce oxygen levels which make conditions difficult for other organisms to survive (Bennett et al., 2017). Consequently, there would be indirect and (depending on severity) direct impacts on all ES categories (Yeakley et al., 2016). For example, a direct impact would include a decline in fish populations in the River Dee with consequential indirect impacts on tourism and recreation; and thereby local business income.

However, seasonal increases in primary production and vegetative growth are expected as temperature increases in spring and summer. In September and October however, other influences including low flows (intensifying nutrient and Chl-a concentrations) and land management (poaching and exposure of field drain) may be having an impact on Chl-a. Supporting ES are fundamental to the functioning of other ES (highlighted in Figure 5.15, page 133) and therefore higher Chl-a concentrations could influence water quality regulation, provision of ecological conditions for higher trophic organisms and fish populations. The knock-on impacts on other ES emphasises the need to manage supporting ES effectively to have benefits that will in turn, enhance another ES. Similarly, the source-pathway-receptor approach can be applied here where the ‘source’ is the supporting ES and if this element is managed effectively, the subsequent ‘receptors’ (i.e. other ES) will improve. Despite being a simplified theory, many factors contribute to ES functioning.

Inferences between Chl-a influences, concentration and linkage with other ES in this study provide an overview and possibilities. The Environment Agency (2016) recognise the requirement of utilising Chl-a to measure ecological responses and understand the risk of eutrophication in rivers. Conversely, several studies (Chambers et al., 2012; Morgan et al., 2006; Royer et al., 2008) suggest assessment of sestonic (water column) Chl-a is not an adequate measure of nutrient related conditions of smaller streams as shading has a dominant influence on concentrations. The study of eutrophication in lotic systems is inadequate compared to lentic systems and there is a clear requirement for further research in understanding the linkages of Chl-a to ES at different spatial and temporal scales. This study however, corroborated with literature and highlighted likely influence of shading, stream temperature, rainfall and antecedent conditions on Chl-a concentrations; and inferred the possible impacts on ES.

Suggested management measures for this study's experiment sites to achieve Yeakley et al. (2016) headwater SPA dilution, purification and nutrient retention are as follows:

- Less nutrient input to the landscape for fertilisation;
- Improved land management practices to enhance soil retention of water (and storage/processing of nutrients) and minimise surface runoff;
- Measures to intercept hydrological pathways and filter nutrients (and sediment); and
- Measures to limit stream temperature and mitigate excessive algal growth, which can deplete oxygen levels and affect the ecosystem.

### *7.5.4 Limitations of algae experiments*

This research uses inferences to highlight relationships to other ES by creating a simplified framework based on literature. It is high-level and strategic rather than specifically quantifying the cascading impact of Chl-a on ES. It is therefore necessary to be explicit and recognise that the ES framework for Chl-a does require substantial additional research to provide quantification. A familiar issue with an ES approach is the intensive resources required to fully quantify and value each process (Costanza et al., 2017). The ES approach remains on the periphery of policy and decision making due to the lack of coherence in methods of estimation and lack of data (Costanza et al., 2017).

This algae experiment could be improved by obtaining fertilisation dates from farmers and monitoring land management changes at smaller timesteps to identify the point of change. Furthermore, as sestonic algae are transported downstream, the algae torch could have been used at sites further downstream to make larger scale assessments. This would, however, require more time, access permissions and an added degree of complexity from larger scale influences.

The algae experimental approach is limited in several ways. Despite using the resources available (algae torch), there are contradictory findings as to whether sestonic algae are an appropriate indicator to nutrient conditions (Chambers et al., 2012; Royer et al., 2008). These contradictions have contributed to the reason why no set methodology for assessing Chl-a in lotic systems has been established for Europe (Carvalho et al., 2002; Newman et al., 2005). Nevertheless Chl-a are effective early warning indicators of environmental degradation (Larned, 2010).

A further limitation is the use of the algae torch and the uncertainty in the ability to accurately measure sestonic algae. It has been previously demonstrated to be affected by light variability at different times of day (Kaylor et al., 2018).

Nevertheless, this aspect of the thesis was an attempt at utilising an interdisciplinary approach to assess multiple benefits of riparian buffer strips and make a comparison between ecological quality of a buffered and non-buffered site, which was achieved.

## 7.6 Catchment-wide riparian buffer strips and flood risk

This study addressed RQ3 by assessing the application of various riparian buffer strip widths at catchment scale and compared the effectiveness of grass and tree-based buffers on reducing peak flow and delaying Ttp. This examined the impact of riparian buffer strips on flood regulation (ES) at catchment scale (Figure 1.1, page 4).

### *7.6.1 Impact on time to peak*

At hourly resolution, the Ttp did not change for any event under all scenarios tested. There are two possible explanations: the delay in Ttp may be less than one hour or the model is unable to represent time delays at this spatial and temporal scale (73 $km^2$ and hourly, respectively). SWAT can conduct sub-daily simulations of flow at a minimum of hourly time step (Jeong et al., 2010) but precipitation can be entered at any resolution from one minute upwards. Although, Bauwe et al. (2017) ascertained the use of variable precipitation resolutions did not affect daily outputs and thereby lower (<1 hr) resolution of precipitation was not required. There are no other studies which test this same influence on sub-daily (hourly) flow outputs. SWAT is therefore not an appropriate tool to assess the delay in Ttp of riparian buffer strips in the Tarland catchment as it is unable to provide flow outputs at a resolution <1 hr. Furthermore, unless observed flow data is measured at < 1 hr resolution, it is unlikely a corresponding model can be calibrated at < 1 hr temporal scale. The scale of the Tarland catchment (73 $km^2$) may also be a factor in model functionality for predicting Ttp changes whereby the spatial extent is too small for the model to register delays in peak flow.

### *7.6.2 Most effective buffer strip width and vegetation type at reducing peak flow*

Part of RQ3 was establishing the most effective width of riparian buffer strip and whether grass or trees were more effective at reducing peak flows. The 50 m tree-based buffer strip scenario was highlighted to be the most effective width and vegetation type, reducing Qpk at all spatial scales on average by ~9% (Table 7.3). Initial boxplot results were the first indication that the difference between tree and grass-based buffers was negligible for the 10 m, 20 m and 30 m width scenarios but began to show a difference in the 50 m scenario. The CN2 values also reflected the similarity between the grass and tree scenarios, albeit not the distinctive difference in the 30 m scenario. Further illustrated by Table 7.3, the average %↓Qpk remained relatively similar for all buffer width and vegetation scenarios until the 50 m tree-based buffer where the largest difference between grass and trees was evident (highlighted in green).

Table 7.3. Average percentage (%) reduction in peak flow (Qpk) for each buffer width and vegetation scenario. Lower standard deviation represents less uncertainty. Greatest difference between grass and tree-based buffer width scenarios are highlighted in green. The highest % reduction in Qpk are in bold.

| | | ***10 m*** | | ***20 m*** | | ***30 m*** | | ***50 m*** | |
|---|---|---|---|---|---|---|---|---|---|
| | | ***Grass*** | ***Tree*** | ***Grass*** | ***Tree*** | ***Grass*** | ***Tree*** | ***Grass*** | ***Tree*** |
| Upper (Netherton) | Average % reduction Qpk | 9.1% | 9.2% | 8.9% | 8.9% | 9.1% | 9.2% | 9.2% | **9.8%** |
| | Standard deviation | ±3.6% | ±3.6% | ±3.6% | ±3.6% | ±3.6% | ±3.6% | ±3.6% | ±3.7% |
| | Range %Qpk reduction | 2.1-17.1% | 2.1-17.1% | 2.1-16.7% | 2.1-16.7% | 2.6-17.1% | 2.6-17.1% | 2.6-17.1% | 2.6-17.5% |
| Middle (Coull) | Average % reduction Qpk | 6.9% | 7.3% | 7.3% | 7.3% | 7.5% | 7.6% | 7.4% | **9.1%** |
| | Standard deviation | ±2.9% | ±2.9% | ±2.9% | ±2.9% | ±3.0% | ±3.0% | ±2.9% | ±3.2% |
| | Range % Qpk reduction | 2.3-13.6% | 2.4-14% | 2.4-14.1% | 2.4-14.1% | 2.5-14.5% | 2.5-14.5% | 2.4-14.6% | 5-16.6% |
| Lower (Aboyne) | Average % reduction Qpk | 7.2% | 7.5% | 7.5% | 7.5% | 7.7% | 7.7% | 7.8% | **9.5%** |
| | Standard deviation | ±3.0% | ±3.0% | ±3.0% | ±3.1% | ±3.1% | ±3.1% | ±3.1% | ±2.5% |
| | Range % Qpk reduction | 3.6-17.3% | 3.8-17.4% | 3.8-17.7% | 3.8-17.9% | 3.8-18.2% | 3.8-18.2% | 3.8-18.5% | 5.6-17.9% |

The 50 m tree-based buffer scenario reduced %↓Qpk on average by only 0.6% more than the 50 m grass-based buffer scenario in the upper catchment (Table 7.3). At the middle and lower catchment scale, the 50 m tree-based buffer scenario reduced %↓Qpk by ~1.7% more than the 50 m grass-based buffer strip (Table 7.3). However, the difference in %↓Qpk for trees and grass were minimal for all other width scenarios and therefore, the cost-benefit of implementing trees over grass may not be a worthwhile approach. Furthermore, farmers may be more likely to incorporate wider grass-based riparian buffer strips, rather than tree-based (McLean et al., 2015; Spray et al., 2015; Zinngrebe et al., 2017). This may encourage more farmers to implement wider riparian buffer strips as it would provide more flexibility for future changes in subsidies. A recent publication from Centre of Ecology and Hydrology (CEH) (Stratford et al., 2017) indicated modelled studies found increased tree cover reduced fluvial flood peaks; whereas some observational studies reported either no influence or reduced peak flows for smaller flood events but no influence on larger flood events. It remains uncertain as to the effectiveness of trees on reducing flood peaks as well as the timescales for trees to become effective.

A study by Spray et al. (2015) found farmers' preferred riparian trees as an NFM measure to implement. Any NFM measure resulting in the loss of profitable land was not preferential. Similarly, McLean et al. (2015) highlighted farmer caution towards NFM measures which would remove land from production for lengthy periods, specifically tree planting. The 50 m tree-based riparian buffer strip had the greatest reduction in Qpk in this study but based on the studies by Spray et al. (2015) and McLean et al. (2015) is unlikely to be welcomed by farmers for the following reasons:

- SRDP provides subsidies for the protection of water margins by using riparian buffer strips up to 12 m wide on steep slopes (Scottish Government, 2016). Increasing buffer width to

50 m would likely remove land from productivity and would not be eligible for subsidy payment.

- The removal of productive land due to increased riparian buffer width and planting with trees would make the land less adaptable for future land management priorities ((McLean et al., 2015; Zinngrebe et al., 2017). McLean et al (2015) highlighted farmer concern over adaptability of their land, as subsidised priorities change with governmental (office) changes (which can be every four years). With the imminent UK departure from the European Union, farmers are unlikely to utilise trees to maintain the adaptability of their land.
- Across the EU, the Ecological Focus Areas element of Common Agricultural Policy which promotes buffer strip implementation has been criticised by farmers. In Germany for example, a study by Zinngrebe (2017) indicated farmers felt the conditions of funding for riparian buffer strips were too complex and they would avoid implementation. Funding was only available for buffer strips up to 20 m wide. In Denmark, the compulsory 10 m buffer of all water bodies has been retracted due to the acknowledgement of a targeted approach being required (Stutter et al., 2019).

**Effective widths of riparian buffer strip**

This study considered the impact of catchment-wide buffer strips of varying width on the reduction of Qpk, at different spatial scales (upper, middle and lower catchment), to ascertain their applicability as an NFM measure. Considering the grass-based buffer strips, results illustrated similar %↓Qpk for all width scenarios when assessed at each spatial scale (as shown in Table 7.4). Therefore, this study advocates the implementation of 10 m grass-based scenarios rather than widths >10 m as it achieves a similar %↓Qpk based on SWAT scenarios. Adopting a 10 m width grass buffer strip would mitigate against farmer concerns of adopting riparian buffer strips, allowing their land to remain adaptable (unlike the use of trees) and minimise the removal of productive land. As proposed by Quinn et al. (2015), utilising ~5% of productive land to slow or store runoff could be an effective proportion of rural catchments to enable a balance between agricultural production and effective catchment hydrological functions. Adopting a 10 m catchment-wide grass-based buffer strip in Tarland equates to 2.1% of the catchment and is estimated to reduce Qpk, on average, by 7.2% at catchment scale. Using the Quinn et al. (2015) approach of ~5% of the catchment, in Tarland a further 2.9% could be utilised to address site specific runoff issues.

Table 7.4. Average percentage (%) reduction in Qpk, area of buffer coverage and average catchment curve number (CN2) for grass-based buffer strip width scenarios.

| | | ***10 m Grass*** | ***20 m Grass*** | ***30 m Grass*** | ***50 m Grass*** |
|---|---|---|---|---|---|
| Upper (Netherton) – 25.3 km$^2$ | Average % reduction Qpk | 9.1% | 8.9% | 9.1% | 9.2% |
| Middle (Coull) – 24.3 km$^2$ | Average % reduction Qpk | 6.9% | 7.3% | 7.5% | 7.4% |
| Lower (Aboyne) – 18.2 km$^2$ | Average % reduction Qpk | 7.2% | 7.5% | 7.7% | 7.8% |
| Catchment scale – 67.8 km$^2$ | Spatial area of catchment land use change (km$^2$) | 2.1 | 4.1 | 6.2 | 10.2 |
| | Average catchment CN2 | 51.58 | 51.42 | 51.43 | 51.42 |

Nevertheless, this uniform approach does have caveats. Several studies (Collins et al., 2010; De Sosa et al., 2018b; Hoffmann et al., 2009; Mander et al., 2017; Stutter et al., 2012) concur on the requirement for flexibility in buffer width application that accounts for site specific conditions such as: topography, soil type and land use. Stutter et al. (2012) highlighted the generic application of rudimentary buffer widths by agri-environment schemes are unable to address site specific problem areas of pollution where larger buffer strip width is required. This emphasises the requirement for buffer strip width to be considered in terms of multiple disciplines in which they serve a purpose (pollution control (including sediment trapping), NFM and biodiversity). Hénault-Ethier et al. (2017) supports this perspective and advocates it is essential to understand spatio-temporal heterogeneity of a catchment to ascertain the most effective buffer strip solution.

Current riparian buffer strip literature which assessed buffer width efficiency concentrate on nutrient and sediment retention rather than hydrology (Mander et al., 2017). Thus, the 10 m grass-based buffer strip is advocated with the understanding that an element of ground-truthing and site-specific assessment (of all relevant disciplines) would be required to fully ensure catchment-wide riparian buffer strips are altered accordingly. For example, considering variable buffer strip widths (whereby shorter width higher up the slope is compensated by increased width at the lower field corner) may force overland flow to engage with the buffer strip (depending on topography). This would provide a larger surface area of vegetation for attenuation where the greatest amount of runoff and sediment is directed to.

The field experiment in this study is prime example whereby the model results demonstrated (uniform width) buffer strips can reduce Qpk, but at field scale, bespoke targeted and variable buffer width placement were recognised to potentially improve surface runoff attenuation in the field corner. As proposed by Phogat et al. (2019), adjacent crop types, management and rotational regimes, and preferential flow paths need to be considered at hillslope scale to determine the most effective width of buffer to use and whether it should vary in width. The contrast between field and modelled results highlight SWAT may be unable to represent the novel and bespoke solutions identified at field scale to improve efficiency of buffer strips. Modelling approaches to incorporate the ability to identify bespoke management measures requires further development. Thus, a sensible and practical approach to interpreting field and model results is necessary.

### *7.6.3 Spatial scales and return periods of effectiveness*

The effectiveness of catchment-wide riparian buffer strips on reducing Qpk was examined at three spatial scales: upper (25.3 km$^2$), middle (24.3 km$^2$) and lower catchment/catchment scale (18.2 km$^2$). This was complimented by assessing the size of high flow event (return periods and percentile flows) in which the riparian buffer strip scenarios were most effective at reducing Qpk (See Chapter 6, Section 6.7.5 for modelling results).

As buffer width increased, the area of land covered also proportionately increased in each sub-catchment (Table 6.4, page 152). This coincided with reducing average catchment CN2 (which indicates incremental catchment storage). Yet, the average %↓Qpk only reflected this cumulative scenario coverage at the whole catchment scale (Figure 7.2). Desynchronization of flood peaks were not tested and could be an influence in these results. Furthermore, the analysis of return periods (discussed below) showed a clearer relationship between Qpk and %↓Qpk at whole catchment (Aboyne) scale with greater certainty than at other spatial scales). This may be the influence of thresholds where the buffer scenarios are more, or less, effective (for example, return periods or event conditions, and simultaneous influence of soils and land use).

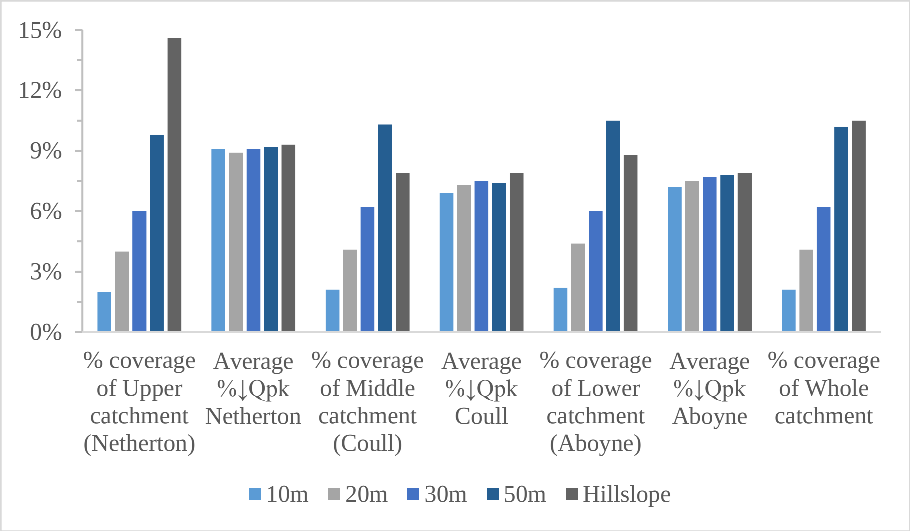



Figure 7.2. Comparison of percentage (%) coverage of land for each scenario and the average % reduction in peak flow (%↓Qpk). The whole catchment is the only example where incremental buffer scenario land coverage is reflected in %↓Qpk.

Figure 7.2 indicates confounding factors other than location on a slope or proximity to the river in which trees impact Qpk. In the upper catchment for example, hillslope trees cover 4.8% more landscape than the 50 m riparian tree scenario; yet the %↓Qpk is similar to that achieved by the riparian trees (Figure 7.2). Soils overlaid by the 50 m tree buffer scenario are predominantly freely draining mineral alluvial soil and brown forest soil whereas; the hillslope tree scenario redistributes the trees from mineral alluvial soils to overlay more humus-iron podzol and peaty podzol soils (Appendix 1). The peaty podzol is considered to have 'slow' infiltration and thereby would induce more runoff. The hillslope scenario indicates the role of soils and land uses in reduction of Qpk when trees are implemented. Thus, consideration of soil types being overlaid, and land uses being replaced by riparian buffer strips should be considered prior to implementation. Despite being situated on sloping land with more trees in each sub-catchment compared to the 50 m tree buffer scenario, the hillslope tree scenario did not reduce Qpk as effectively as the 50 m tree-based buffer scenario. Thus, model results suggest underlying soils can have a counteractive effect on tree planting for runoff reduction, even on hillslopes. The study by Soulsby et al. (2017, 2015) and Tetzlaff et al. (2014) provided evidence of this by demonstrating land use (i.e. tree coverage), in isolation, was unable to mitigate flooding due to soil saturation and limited groundwater storage.

The Dee catchment in Scotland, which is substantially forested compared to other Scottish catchments, experienced unprecedented flood peaks.

Similarities between SWAT and field experiment results are apparent in relation to soils. SWAT results suggest underlying soils are counteractive to the effectiveness of trees in reducing peak flow. In parallel, the field experiment observations demonstrated soil compaction (and microtopography) of tramlines and machinery tracks diverted flow away from the riparian buffer strip, compromising its function of receiving and attenuating overland flow. Both the model and field results indicate the importance of soils in buffer strip effectiveness and concur with recommendation of Hallett et al. (2016) to prioritise further studies to examine the impact of soil degradation on flooding.

Highlighted in Table 7.3 across all scenarios, Netherton had the highest %↓Qpk, Coull had a lower %↓Qpk compared to Netherton, and Aboyne %↓Qpk improved and was higher than Coull. A spatial distinction between %↓Qpk in the upper, middle and lower catchment was evident. Considering each sub-catchment independently, Table 6.5 (page 155) demonstrated coniferous and rough low productivity grassland land uses replaced by the buffer scenarios followed this same trend: higher in Netherton, lower in Coull, and higher in Aboyne. When assessing the cumulative areas of land use replaced by the buffer scenarios (Appendix 1), acid grassland was additionally highlighted to follow this same trend. Again, land uses replaced by the buffer scenarios are shown to influence the degree of Qpk reduction. The influence of replacing coniferous trees with either grass-based or tree-based buffers on Qpk reduction is uncertain. For example, coniferous trees would be replaced by deciduous trees in the tree-based buffer scenarios, therefore the loss of trees is negligible. In the model setup, these land uses are attributed the same parameters, however this could be an element of uncertainty in the parametrisation of the land uses in SWAT.

The land uses removed by implementing the scenarios would also have implications for runoff and drainage. The buffer width scenarios generally expelled improved grassland, but also arable land and acid grassland (Appendix 15). Improved grassland and arable land are intensely managed land uses which were reflected in the soil attributes assigned to them in the model setup (Appendix 6). This would explain the reduction in Qpk by each of the buffer width scenarios. Intensely managed land is replaced by non-intensive land use on freely draining soils, where infiltration can be enhanced by more permanent vegetation and catchment storage is increased, likely through a change in CN2. The numerical interaction in SWAT between land uses (including buffer scenarios), soils and the event conditions makes it challenging to definitively identify one aspect which has an overriding influence. Nevertheless, improved grassland, arable land and coniferous land uses were, respectively, the most dominant land uses replaced by the buffer scenarios across the catchment. Coincidently, mineral alluvial soils, humus-iron podzols and brown forest soils, respectively, were the dominant soils overlaid by the buffer scenarios. In combination with high flow events and event conditions, these catchment conditions resulted in an average %↓Qpk of 9.1% at Netherton, 6.9% at Coull, and 7.2% at Aboyne when the 10 m grass-based buffer scenario was applied.

Across all spatial scales and return periods, the 50 m tree-based buffer strip had the highest (average) %↓Qpk as illustrated in Figure 7.2. Interestingly, as spatial scale increased, impact on Qpk decreased towards the lower catchment during QMED, 1 in 2 and Q30 events (Appendix 16). Although this applies to >1 in 10 event and the inverse is evident for 1 in 5 and Q10 events, a greater number of events are required to increase confidence in the respective trends. There are a greater number of QMED, 1 in 2 and Q30 events, which increases certainty in the dissipation of impact on Qpk reduction at larger spatial scales. Albeit, Aboyne showed greatest standard deviation for a 1 in 2 return period (Appendix 1), indicating less confidence.

The 50 m tree buffer consistently demonstrated the highest average %↓Qpk (Appendix 16) for all return periods and at all spatial scales. In comparison to the %↓Qpk achieved by the 10 m grass buffer, the land required for each scenario (2.1% and 10.2% of the catchment, respectively) highlights the additional %↓Qpk achieved by the 50 m scenario does not seem an adequate proportional gain. Thus, the 10m grass-based scenario is advocated for this reason and due to the greater likelihood of improved farmer uptake (as discussed in Section 7.6.2).

Overall, reduction in Qpk at higher return periods was uncertain at all spatial scales. At lower return periods (Q30, 1 in 2 and QMED), model results demonstrated:

- A smaller spatial scale (e.g. upper catchment), the reduction in Qpk was larger but with greater uncertainty.
- At larger spatial scale (e.g. middle to lower catchment) the reduction in Qpk was smaller but had greater certainty (respectively).

As illustrated by the comparison of the field experiment scale of SWAT outputs (Section 6.3.1), SWAT is purposely designed for larger spatial scale assessment (Arnold et al., 2010) and the poor representation of flows at the experiment site (Figure 6.3, page 150) illustrate SWAT is not appropriate for analysis at such small spatial scale (0.33 km$^2$).

### *7.6.4 Issues of scaling between field and catchment scale*

The results of this study demonstrated the disconnect between field results and catchment scale model results. Field scale observations demonstrated a complex interaction between microtopography, overland flow paths and the functionality of the riparian buffer strip on a hillslope. In this respect, SWAT was unable to identify such small spatial scale distinctions in overland flow paths. The resolution of the DTM (1 m) contributes to this issue however the mathematical functions of SWAT were unable replicate small scale overland flow distinctions; evidenced by the inability to adequately represent flows at experiment site scale (Figure 6.3, page 150). Nevertheless, the purpose of SWAT was to assess the landscape scale implementation of riparian buffer strips and was fit for this purpose. Furthermore, the scaling issue was apparent in the differing conclusions of the field experiment and the model. SWAT results highlighted the uniform buffer strip width (applied catchment wide) effectively reduced peak flows. Yet, the field experiment observed the requirement for altered design of riparian buffer strips on hillslopes, whereby targeted variable widths were necessary to improve NFM functionality. The capability of field scale observations to identify localised improvements supports the requirement for model outputs to be verified at specific sites.

These findings concur with a longstanding challenge of scaling in hydrological modelling (Blöschl, 2001; Blöschl et al., 2019; Blöschl and Sivapalan, 1995; Rajib et al., 2018). Processes are known to transition between (hillslope, catchment and regional) spatial scales (Blöschl and Sivapalan, 1995; Langhans et al., 2019). Unrealistic representation of small scale stream flows is common within a semi-distributed hydrological model adequately representing catchment scale stream flows (Baffaut et al., 2015; Rajib et al., 2018). A recent synthesis (Blöschl et al., 2019) highlighted the following unsolved challenges in hydrology regarding spatial scale:

- How do the catchment scale hydrological laws change with scale?
- What are the reasons for spatial heterogeneity in runoff?
- “Why is most flow preferential across multiple scales?”

These challenges are additionally hindered by the complexity and multitude of factors that affect hydrology all spatial scales. Continual evolution of the spatial heterogeneity of land use, land management, soils and rainfall distribution add multidimensional complexities. For example, Langhans et al. (2019) highlighted the lack of consideration for runoff coefficients varying with increasing field sizes in models, especially in relation to the effects of crop type and tillage on coefficients. Scaling in hydrological models remains a prominent topic requiring model development and improved understanding of hydrological process evolution at different spatial scales. Nevertheless, hydrological model outputs are useful strategic tools at larger spatial scales and verification of results at field scale is important.

### *7.6.5 SWAT critique: limitations and uncertainty*

Like any physically based hydrological model, SWAT provides runoff predictions based on perceived complex hydrological processes and achieves this by the use of extensive parameters (Beven, 2012). There are many parameters in SWAT and this study adopted the use of default parameters for land use which have their own uncertainties. The complexity of SWAT parameterisation can allow highly specific definition of crop type with leaf area index (LAI), rooting depths, biomass and harvesting regimes. As highlighted by van Griensven at al. (2012), limited studies deviate from the use of default crop/land use parameters, but often this information is not available, or would be costly and time consuming to obtain. The default parameters have their own uncertainties, but the land use defaults were used in this study in the absence of data.

The level of detail able to be captured by SWAT can be perplexing to novice users; Beven (2012) concurs with this view and proposes SWAT is over-parameterised. However, using SWAT enabled detailed spatial representation of soils (for which detailed soils data existed) and therefore an improved representation of hydrological processes. This study agrees with Beven (2012) in that there was a trade-off between embracing a detailed parameterisation approach, time constraints, data constraints and uncertainty. An initial understanding of SWAT clarified the importance of soil parameterisation for the catchment, as this was a crucial hydrological partitioning medium in the model. The soils data inputs were comprehensive for the Tarland SWAT model and did not use any hydrological default values or soil profiles supplied by the SWAT database. Nevertheless, soil parameters were sensitive in the calibration process and available water content (SOL_AWC) and soil hydraulic conductivity (SOL_K) had to be altered. This was also the case for some CN2 values (in daily calibration). There is an uncertain element as to whether the results are less about land use change and more about the changes to curve numbers (CN2) and other storage parameters such as soil water content and soil hydraulic conductivity and how these coincide with each other alongside slope classes. Considering the detail of soils data input (albeit with its own uncertainties based on HOST), the uncertainty of SWAT model and possible interaction of parameter changes compensating for structural model errors (Beven, 2012) was becoming clearer.

The importance of soil properties and precipitation inputs are highlighted by Boithias et al (2017). Several studies (Bieger et al., 2014; Sexton et al., 2010; Zabaleta et al., 2014) inform of the influence of inaccurate precipitation data as a result of the use of rain gauges that are not spatially representative of the catchment and inaccuracies in precipitation observations (e.g. undercatch caused by wind (Pollock et al., 2018), or prevailing storm directions). These studies emphasise the importance of precipitation input to improve model predictions (Gassman et al., 2014). The use of the Aboyne station in this study may not be fully representative of the upper higher elevations in the catchment. The uncertainty can be generated by using substitute weather stations for precipitation data. Replacement of missing Aboyne precipitation data accounted for 1.9% and introduced uncertainty, albeit a minimal percentage of the overall dataset (23 years). Nevertheless, these inputs may have coincided with events and had an impact on runoff volumes and peak flows if they were not representative.

Boithias et al. (2017) and Jeong et al. (2010) identify timestep of the model to dictate sensitive parameters. At sub-daily resolution, main channel hydraulic conductivity (CH_K2) and main channel roughness Manning's *n* coefficient (CH_N2), which are channel routing parameters, are most sensitive (Boithias et al., 2017; Jeong et al., 2010). At daily resolution, groundwater parameters are most sensitive (for example, the threshold groundwater depth required for return flow to the channel to occur; GWQMN). This was also the case for this study and proposed by Boithias et al. (2017). The sub-daily sensitive parameters influence Ttp as channel roughness and hydraulic conductivity dictate flow velocities. For SWAT to be effective (at estimating riparian buffer strip influence on Ttp), these sensitive parameters and the ability to generate flows at <1hr timesteps, are required to improve its applicability in Tarland for estimating Ttp changes. Nonetheless, the purpose of this study was primarily to ascertain the impact of buffers on peak flows and this was achieved using SWAT.

This study had a maximum of 1810 HRUs (which reduced as buffer widths increased). HRUs define the different homogenous zones of specific land use, soil and slope within each sub-basin of a catchment. As well as assuming HRUs are homogenous, Beven (2012) criticises large numbers of HRUs as a reduction of runoff in one HRU can be compensated by an increase in another, a further uncertainty. However, the use of HRUs in this study is more appropriate as a lumped model would be unable to represent the vast diversity of buffer placement above various soil types and slopes.

The use of SWAT at the sub-daily resolution and understanding how calculations are adapted is unclear in literature and SWAT documentation. Without having experience of mining source codes, the differences between daily and sub-daily calculations requires more transparency for users. Jeong et al. (2010) alludes to parameters estimated on a daily basis being equally distributed for each timestep (which for this study was 24 hours) with exception to precipitation data, as this was applied at the hourly timestep.

Tarland SWAT model utilised the NS statistic as an objective function to ascertain the goodness-of-fit to a 1:1 line between observed and simulated flow data (Moriasi et al., 2007). There are criticisms by Beven (2012) and Krause (2005) of NS and the squared values of difference between observed and simulated data, leading to overpredictions in high values and under predictions in low values. This can lead bias for peak flows (Arnold et al., 2012b; Beven, 2012; Krause et al., 2005). Given this study was focused on peak flows, this is less relevant and enables them to be replicated. Although, NS and R2 were used in this study and introduced uncertainty of model performance, Beven (2012) contended that *all* objective functions have their relevant uncertainties. Moreover, the most common reported statistics in SWAT publications are NS and $R^2$ and is concurred by numerous studies (Gassman et al., 2007, 2014; Merriman et al., 2018; Piniewski and Okruszko, 2011; van Griensven et al., 2012), hence the adoption of objective function to enable comparison to other studies.

Nonetheless, advances in developing SWAT are progressing. For example, Raj et al. (2018) are exploring the adaptation of the vegetated filter strip (VFS) module in SWAT to facilitate routing of water, thereby increasing availability of infiltrated water for vegetation uptake: VFS currently does not affect hydrology (Arnold et al., 2012a) and therefore was not used to represent riparian buffer strips in this study. SWAT is also being completely revamped into SWAT+, which will improve source codes, model capabilities, landscape discretisation and flow routing (Bieger et al., 2017).

## 7.7 Riparian buffer strips as an NFM measure: linking field experiment and modelled catchment scale

This study utilised an ES approach to assess the ability of a riparian buffer strip on a hillslope to provide multiple ES and, in turn, perform as an NFM measure. Flood regulation was examined in terms of overland flow attenuation (at field scale) and peak flow reduction (at catchment scale); whereas an indication of nutrient cycling and primary production conditions (ecological quality) at field scale was achieved by monitoring algae biomass (Figure 1.1, page 4). This section summarises discussion points from this research to conclude whether the riparian buffer strip in this study functioned as an NFM measure.

### *7.7.1 Interception, attenuation and storage of runoff*

Nine runoff events recorded in the buffer strip indicated overland flow was (on these occasions) intercepted and attenuated by vegetation roughness, which increases infiltration. This demonstrates that the buffer strip was providing NFM functions during these events. However, evidence of overland flow bypassing the buffer strip suggests its functionality is changeable and dependent on:

- Event conditions
- Land management conditions
- Crop cover
- Microtopographies created by tramlines, ploughing and compacted pathways from agricultural machinery

Furthermore, the overland flow path through the centre of the buffer strip concentrated runoff, which can increase runoff velocity. This study considers the riparian buffer strip as an effective NFM measure despite these shortcomings for the following reasons:

- Runoff was able to enter the buffer strip (during nine events) despite the diversion of some runoff due to microtopography.
- Runoff entered the buffer strip during wetter antecedent conditions, as well as high intensity and depths of rainfall during winter when the adjacent field was mostly bare soil.
- Despite overland flow paths through the buffer strip and becoming concentrated to create greater velocity than if the flows were dispersed, the runoff would otherwise have flowed away from the buffer down the (unvegetated) tramline flow path. This could have gathered more sediment, faster velocity and more rapid delivery to the stream.
- These considerations indicate the runoff entering the buffer strip attenuated overland flow more so, than if it were to flow downslope via the tramlines. The buffer had more vegetative cover than the adjacent field, even in winter.

At field (using an experiment) and catchment scale (using SWAT), the riparian buffer strip was concluded to have been an effective NFM measure. The field study recognised the necessity to implement further measures (most importantly a RAF) to maximise interception and storage of runoff. The buffer strip can be made more effective by utilising additional measures (Stutter et al., 2018). Consideration was given to the limitations of the buffer strip when situated on a hillslope and affected by microtopography. The empirical element of this study determined riparian buffer strips to have potential to reduce flood risk. Nonetheless, management of flow paths from adjacent land is required, in conjunction with support from other measures to maximise potential and achieve the greatest reduction in flood risk.

The modelling aspect of this study identified 10 m grass-based buffer strips achieved an average reduction in Qpk of 7.2% at catchment scale. The 10 m grass-based buffer was most effective at the 1 in 5 year return period, with percentage reduction Qpk increasing incrementally from 7% to 8.4% from QMED, 1 in 2, Q30 to 1 in 5 year return period. Albeit, the 50 m tree-based buffer scenario had the greatest average percentage reduction in Qpk (11%). The 10 m grass-based scenario was preferred due to considerations of land coverage, practicalities of implementation, and the magnitude of Qpk reduction; compared to the tree-based or wider buffer scenarios.

Overall, the model identified catchment wide 10 m grass-based buffer strips to be an effective flood management measure as they reduced Qpk on average by 7.2% (likely due to increased storage capacity created by the changing CN2 values of different land classes). The field study also demonstrated the buffer strip attenuated runoff but requires design considerations and additional measures to improve runoff attenuation. Both the field experiment and modelling outputs confirmed riparian buffer strips were an effective, notwithstanding imperfect, NFM measure in the Tarland catchment.

### *7.7.2 Multiple ecosystem services*

This thesis demonstrated the seasonal temperature influence on Chl-a concentrations, which were incrementally higher at the non-buffered site. This indicated the riparian buffer strip provided the benefit of shading which, in turn, controls stream temperatures and Chl-a generation (especially in low flows). By controlling Chl-a concentrations in headwaters, this reduces the Chl-a biomass being transported downstream where lower velocities increase residence time and pose a risk of oxygen depletion. Furthermore, significant research exists on the plethora of multiple benefits riparian buffer strips can provide (see Section 2.2.4, page 17). Based on evidence, this study determined the studied riparian buffer strip to have provided the following multiple benefits: riparian shading, runoff attenuation, habitat and wildlife corridor (see Appendix 1 for pictures of wildlife (including a fox, pheasant, various birds and a vole or mouse) captured on the field camera).

The ES approach to this study was a high-level overview of linkages between Chl-a and wider ES based on literature. In retrospect, it offered only a proposal of *possible* interlinkages. The process of formulating the framework highlighted the lack of clarity outlined in numerous studies (Böck et al., 2018; Costanza et al., 2017; Dittrich et al., 2018; Grizzetti et al., 2016; Keesstra et al., 2018; Nesshöver et al., 2017) in methods to quantify ES without cumbersome and expensive data collection; in a way that can be incorporated into decision making. Nevertheless, a recent EU publication on nature based solutions, *ThinkNature* (Lehvävirta et al., 2019) confirms listing ES or multiple benefits is justifiable and useful. This research attempted to undertake a multidisciplinary approach by incorporating flood risk hydrology with ecology, water quality and ES. Despite the benefits in identifying the comparison between a buffer and non-buffered site, the research required more data collection to provide an improved understanding of lotic algae conditions; (and how these interacted with the complex variety of influences) which would have incurred additional costs and resources.

As indicated by this study, the complexity of spatial and temporal scales for multiple influences (e.g. land use, biogeochemical cycling and weather) and multiple environmental (e.g.

river biota); economic and social receptors present a challenge to gain a catchment-wide understanding of how these all interact with one another along the river continuum. Despite the ES concept being a research focus for over twenty years (Costanza et al., 2017), much work has yet to achieved before it can become integrated into decision making.

### *7.7.3 Future recommendations for riparian buffer strip design*

Based on the field experiment, this thesis concurs with previous research which proposed a targeted approach to buffer implementation in terms of width and design (Collins et al., 2009; Hénault-Ethier et al., 2017; Phogat et al., 2019). A key addition to these studies is the consideration of complimenting riparian buffer strips on hillslope with RAF placement in lower field corners to enhance NFM functionality. Adaptive design, targeted widths and supplementary measures have been advocated in this thesis to improve the NFM performance of riparian buffer strips on hillslopes. A one-size-fits-all is less effective and riparian buffer strips need to be tailored to their localised conditions including: adjacent land use, slope, topography, and soil conditions.

A recent publication summarises current studies and highlights a shift towards *designed multicomponent buffer zones* (Stutter et al., 2019) concurring with this study's proposal for variable width riparian buffer strips in the upper catchment. The riparian buffer strip could be wider as it approaches the lower field corner where runoff was pooling and subsidised by a RAF to ensure overland flow (not entering the buffer strip) is intercepted. However a study by Zak et al. (2019) has tested the implementation of an integrated buffer zone with the use of ponds along the toe-slope of an arable field, immediately before the riparian vegetation and the stream (illustrated in Figure 7.3). The design is targeted to intercept tile drainage, surface and subsurface flows with the primary aim to augment the 'dry' buffer zone by removing sediments and nutrients (Zak et al., 2018). This adaptation to riparian buffer strip design is advocated to enhance ES of riparian buffer strips by providing additional flood attenuation and storage, as well as enriching biodiversity (e.g. providing habitat for amphibians), and removing sediments and nutrients (Stutter et al., 2019; Zak et al., 2019, 2018).

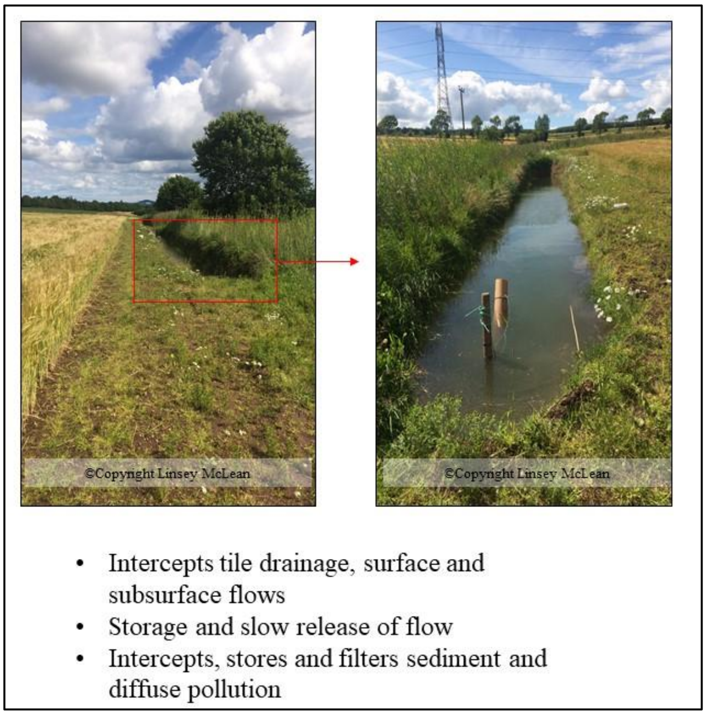



Figure 7.3. Integrated buffer zone implemented for Zak et al. (2019) study.

Previous to the Environment Agency's evidence directory for NFM publication (Environment Agency, 2017a), riparian buffer strips were not explicitly considered an NFM measure. Nevertheless, this study has demonstrated, the NFM qualities of riparian buffer strips (e.g. flood regulation and provision of multiple ES). More literature citing riparian buffer strips and their influence on flood attenuation are emerging, but more evidence is required at field and catchment scale, especially for hydrological properties. Climate change must also be considered and whether riparian buffer strips could become overwhelmed by increased precipitation depths and intensity; or whether their effectiveness improves as growing season extends with warmer temperatures (Wagena and Easton, 2018).

# Chapter 8 Conclusions

## 8.1 Introduction

This chapter provides a research summary outlining the aim of this thesis and key research advances as a product of this work. A synthesis of the findings from this research are provided alongside the research questions to demonstrate how successfully these objectives, and the research framework (Figure 1.1, page 4), were fulfilled. The chapter is concluded with suggested future research.

## 8.2 Research summary

The aim of this thesis was to establish whether riparian buffer strips can be considered an effective NFM measure. Assessing whether riparian buffer strips are effective for flood regulation (reduction in peak flow at catchment scale and runoff attenuation at field scale) and multiple ES (nutrient cycling and primary production) at field scale established NFM effectiveness. The findings of this research have provided the following advances in research:

- Riparian buffer strips located on hillslopes and adjacent to rotational arable land may not be achieving optimum runoff attenuation (and NFM) potential due to overland flow bypassing the buffer strip. Targeted management measures are required to mitigate runoff bypassing the riparian buffer strip and ensuring vehicle tracks, erosion rills (or other microtopography) can be altered to force a flow path into the buffer strip. This may include variable riparian buffer strip width, which targets areas requiring wider buffer strips to attenuate runoff, trap sediment or minimise nutrient transport. Further research is required to quantify whether these supplementary measures to riparian buffer strips result in a reduction of flood risk.
- Hillslope riparian buffer strips can be complimented with temporary RAFs in lower field corners to capture the overland flow bypassing the buffer strip. This could have added benefits for reducing flood risk. If the concept is incorporated into policy (e.g. SRDP), implementing temporary RAFs in field corners may enhance NFM uptake, as riparian buffer strips are an element of farming subsidies (e.g. single farm payment and AECS) which require compliance for payment.
- The comparison of observed overland flow paths and those identified using flow accumulation pathways, (derived from a 1 m DTM) identified the pooling in the field corner with relative accuracy. JHI are now progressing this work and developing a methodology using topographic data and flow accumulation pathways to identify potential field corners for runoff storage, by implementing temporary RAFs in sloping agricultural landscapes. Application across Tarland is in progress (Stutter et al., 2018) and will subsequently be tested in other catchments (Eddleston). This emphasises the

significance of this research. It has informed flood risk science about these overland flow diversions away from hillslope riparian buffer strips and prompted adaptation of a method in this research to develop a strategic tool.

## 8.3 Conclusions

***RQ1: What are the different conditions by which overland flow moves into and through riparian buffer strips?***

*Do riparian buffer strips demonstrate natural flood management merits of runoff interception and attenuation at field scale; and on a hillslope with rotational arable land management in the adjacent field?*

- Overland flow was determined to be generated from the adjacent field by saturation excess. Assessment of event conditions however, identified runoff events coincided with higher values of maximum rainfall intensity. Determination of the dominant overland flow process from the adjacent field would require additional research involving the extensive use of monitoring equipment.
- Overland flow was observed to enter the riparian buffer strip and therefore intercepting overland flow from the adjacent field. This suggests the riparian buffer strip was functioning as an NFM measure as the vegetation inside the buffer strip would attenuate flows.

*Does land management practices or event conditions affect the volume of overland flow entering the riparian buffer strip?*

- The study was unable to identify whether land management or event conditions were more influential on runoff Qpk, runoff volume and contributing area of runoff. Extending data collection over a longer period would enable adequate statistical analysis to determine which aspect has more influence.
- Trend analysis indicated the runoff events with the highest Qpk, runoff volume and contributing area simultaneously corresponded with bare soils in the adjacent field in winter, wetter antecedent conditions; and higher precipitation depth and maximum intensity. An instance of a summer runoff event during drier antecedent conditions and a tall crop in the adjacent field identified maximum intensity as the only condition high enough to explain overland flow occurring.

*Does land management practices or event conditions influence the ability of riparian buffer strips to receive overland flow and attenuate surface runoff?*

- Trend analysis determined the following event condition thresholds which corresponded to runoff events in the riparian buffer strips:
  - Pcp depth ≥20 mm; if <20 mm runoff would occur if API30 was high (e.g ≥70 mm) and or/max intensity was high (e.g. ≥3.2 mm).
  - API30 ≥29 mm; if <29 mm runoff would occur when Pcp depth ≥23.9 mm and max intensity ≥ 3.7 mm.
  - Max intensity >1.8 mm; no runoff occurred when API30 was low (e.g. ≤21 mm) and max intensity was >1.8 mm.
  - Event duration was ≥47 hr; if <47 hr runoff would occur if API30 was high (e.g. ≥31 mm) and/or max intensity was high (≥3.2 mm)
- Antecedent conditions, precipitation depth and maximum intensity demonstrated a dominance in explaining why overland flow would enter the buffer strip when event conditions were under the identified thresholds.
- Tramlines and tracks from farm traffic created microtopography which were observed to cause overland flow to bypass the riparian buffer strip. This created concentrated flow paths running adjacent to the field-buffer interface downslope to the field corner, where overland flow pooled.
- Field observations of these diverted concentrated overland flow paths found runoff to enter the buffer strip when the concentrated flows reached a sufficient depth to spill into the buffer zone. This emphasised the previous thresholds are therefore specific to this site and circumstance; and may not be applicable if concentrated flow paths were disrupted or disconnected. Nevertheless, these thresholds are relevant to this site and represent event conditions when concentrated overland flow paths were deep enough to overspill into the buffer strip.
- Concentrated overland flow paths were observed through the centre of the riparian buffer strip during one heavy rainfall event. Despite higher depths and velocity of concentrated flows, it was concluded attenuation in the buffer strip was greater than that of the bare soil in the adjacent field.
- A method to rapidly assess where microtopographies could be creating concentrated flows and bypassing riparian zones was explored. Assessing accumulated flow paths using the 1 m DTM indicated a similar area of ponding in the field corner. Flow paths were represented but a higher resolution (<1 m) DTM would provide more accurate spatial representation of the microtopographies. In time however, high resolution DTM will become more economically viable, which will allow less restricted access to the data. Present DTM resolution is adequate for high-level strategic assessment of potential RAF implementation locations. Nevertheless, validation by field observation

is required and an understanding that microtopographies could change as rotational arable land undergoes changes throughout the year.

***RQ2: What is the impact of riparian buffer strips on algae biomass in streams as an indicator of nutrient cycling and primary production?***

*Is there a difference in ecological quality ratio between a riparian buffer strip site and a non-buffered site?*

- The buffered site had a higher EQR than the non-buffered site indicating it was in better ecological condition. Despite this difference, both the buffered and non-buffered site EQR were determined as *moderate* status as the EQR values were within the *moderate* score range.
- Chl-a concentrations were used as a proxy to algae abundance and were different between sites for each month of measurements. April, August and November 2014 were the only three months when the Chl-a concentrations were statistically significant.

*How do event conditions affect algae conditions at a riparian buffer strip site and a non-buffered site?*

- Relationships were tested between Chl-a concentrations and event conditions. Although utilised for indication only (as the sample size was low), the non-buffered site illustrated a stronger relationship with stream and mean daily temperature. Thus, suggesting riparian shading had a role in the weaker relationship between the same variables at the buffered site.
- Some disruption to seasonal trends was evident at the buffered and non-buffered site. Land management and event conditions were assessed to explain these disruptions but were unable to clarify specific conditions which may have contributed to the disruptions. However, the non-buffered site Chl-a concentrations increased more rapidly with seasonal change (as temperatures warmed) and at a greater magnitude than the buffered site. The influence of riparian shading was identified as a possible explanation but would require further field measurements to clarify.

*Are there any trends in algae concentrations following land management changes at the riparian buffer strip site?*

- Assessment of monthly land management changes alongside Chl-a concentrations were unable to identify consistent trends to indicate any land management influence on algae. Nevertheless, in August 2014 a substantial decrease in Chl-a at the buffered site corresponded to five fields being harvested, high API30, high pcp depth, and three Q5 events occurred prior to the Chl-a decrease. Flushing of Chl-a from high flows was as a result of these event conditions, emphasised by the lack of response to increased nutrient levels. More research is required to understand the complex interconnectedness between land management, nutrients, flow conditions and algae.

***RQ3: How effective are catchment-wide riparian buffer strips at reducing peak flow and what is the most effective riparian buffer strip width and vegetation type (using SWAT model as a tool)?***

*What width of catchment-wide riparian buffer strip reduces peak flow ($m^3/s$) most effectively at upper, middle and lower catchment scale?*

- Notably, all buffer scenarios reduced peak flow at all spatial scales. The 50 m tree-based scenario resulted in the greatest average reduction in peak flow across all events.
- The 50 m tree-based buffer scenario had the greatest average %↓Qpk (11%) and covered 10.2% of the catchment. The average %↓Qpk for the 10 m grass-based buffer scenario was 7.2% and covered 2.1% of the catchment. Despite the highest peak reduction being achieved by the 50 m tree-based scenario, the 10 m grass-based scenario achieves (on average) a greater percentage reduction in peak per $km^2$ covered in the catchment.
- At each spatial scale, there was limited difference between the 10 m, 20 m, 30 m and 50 m widths and between the vegetation type. The average percentage reduction in peak flow was sustained at a similar value, per spatial scale, regardless of vegetation type.
- Greatest reduction in peak flow occurred in the upper catchment and as spatial scale increased, the reduction in peak flow decreased at the middle and lower catchment, respectively. Nevertheless, the upper catchment peak flow reductions were more uncertain. As spatial scale increased, the uncertainty in peak reduction reduced.
- Event conditions were assessed to determine any relationship with reduction in peak flow. API30 was the single condition correlated to %↓Qpk. There was a negative correlation, which was weak in the upper catchment but became stronger with increasing spatial scale. The correlations were significant and indicated drier antecedent conditions corresponded to larger reductions in peak flow.

*Do grass-based or tree-based riparian buffer strips provide a greater reduction in peak flow?*

- There was limited difference between grass and tree scenarios in their ability to reduce peak flow. However, the 50 m width scenario demonstrated a difference in %↓Qpk for the grass and tree-based buffers at the 1in 2 year return period for the upper catchment and for QMED in the middle and lower catchment. The distinction between grasses and trees was more prominent in the middle and lower catchment.

- The placement of the trees was explored to establish the impact on peak flow when riparian trees were redistributed on upper hillslopes of the catchment. The riparian trees had a larger reduction in peak flow and the difference between the scenarios increased as spatial scale increased. There was a 0.6% difference in %↓Qpk in the upper catchment, a 1.2% difference in the middle catchment and 1.6% difference in the lower catchment.

## 8.4 Recommended further research

Suggested areas of research to be progressed out with the scope of this thesis include:

- The overland flow field experiment in this study could be replicated on a larger scale across various locations in a catchment. These locations may reflect different slope and topography, as well as different land uses and soils. Understanding how riparian buffer strips function as an NFM measure at a larger spatial (and temporal) scale (supported by empirical evidence) will be required to inform policy and encourage catchment-wide implementation.
- This study could similarly be replicated by utilising instrumentation which can adequately quantify hillslope processes, daily land management changes and the interaction between subsurface and surface hydrological processes on a hillslope; which are interlinked to the effective NFM functionality of riparian buffer strips.
- This study identified the influence of microtopography, tramlines and vehicle tracks on overland flow paths on a hillslope. Further work in this area of research is suggested to determine design and management considerations for riparian buffer strips to maximise their ability to receive overland flow. Possibilities include management of adjacent land to encourage runoff to enter the riparian zone.
- The effectiveness of riparian buffer strips as an NFM measure on a hillslope could be improved due to diversion of overland flows. This research suggested intercepting diverted flows by implementing a temporary RAF in the field corner, to enhance runoff attenuation. Future research exploring the effectiveness of this paired NFM measure approach is suggested to determine the impact on flood risk at various spatial scales. Hydrological modelling and field monitoring in relevant paired catchments may be utilised.
- Understanding the role of adjacent land management in relation to riparian buffer strips effectiveness at attenuating runoff could potentially indicate any minor changes to land management practices required to enhance buffer functionality.
- Establishing a uniform riparian buffer strip width has been demonstrated in the literature review and discussion, to be less effective and arbitrary. Further research to ascertain methodologies and tools to identify the location of targeted wider riparian buffer strips is required to support acceptance into policy and advocate the adoption of targeted buffer zones in agricultural land. Incorporation of multiple disciplines into these methods and

tools are encouraged to consider WFD objectives, nitrate vulnerable zones and sediment transport issues; to ensure a targeted width riparian buffer strip has multiple benefits.

- The existing experiment site could remain operational but with improved equipment installation (e.g. more field cameras and a rain gauge at the site). This learning can be applied to adapt the existing site and establish subsequent sites for comparison.
- There is a lack of agreed standardised methodology for utilising the ecosystem services approach and an increasing requirement to understand our environment holistically to encourage sustainable decision making. Further work is required to guide practitioners on how to adopt an agreed ES approach and extensively consider the wider implications of actions and measures implemented (for any sector).

Upon reflection of this research, there were lessons learned and elements, which in hindsight, could be improved if provided an opportunity to repeat the study. These improvements would include:

- Installation of time-lapse cameras at the runoff experiment site to capture daily land management changes. This would allow definitive time stamps on when fields were ploughed and harvested, as well as provide potential snapshots of overland paths during rainfall events. It would further benefit the increase in data availability to assess linkages between land management changes and algae/ES responses.
- A rain gauge at the site would have mitigated the requirement to calculate catchment rainfall and provided greater certainty that rainfall occurred at the site. This would translate as having more events to analyse as these were determined using runoff and soil moisture variables.
- The installation of a third V-flume across the width of the buffer would have allowed concentrated overland flow paths within the riparian buffer strip to be captured and quantified.

Nevertheless, the methods used, especially in relation to the runoff experiment, can be implemented in any location and replicated. The runoff experiment has provided valuable insight into the functionality of riparian buffer strips in relation to attenuating runoff and highlighted potential opportunities to improve their future implementation and effectiveness as an NFM measure.

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# Appendices

## Appendix 1

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# Natural Flood Management in the UK: Developing a Conceptual Management Tool

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**ABSTRACT:** Natural Flood Management (NFM) is increasingly adopted as a crucial element within the UK sustainable flood management strategy. This utilises a non-structural multi-benefit approach, whereby the landscape's natural ability is restored or adapted to reduce flood risk by permanently or temporarily: retaining flood water, providing attenuation, promoting sediment deposition and transport, and adjusting the geomorphology formations of river systems (Flood Risk Management (Scotland) Act, 2009). Despite the drive for NFM, it is well-recognized that there is a significant lack of evidence that NFM techniques are actually effective in reducing flood risk at all scales of (sub-) catchment. Simultaneously, NFM "multiple benefits" require evidence based quantification in order to fully evaluate and appraise NFM techniques as a substitute, or to compliment, hard engineered flood defences. Thus, within the UK the full range of NFM is being specifically assessed for this, and the associated cost-benefit, by way of field monitoring in a number of demonstration catchments but still requires extensive research. The aim of this paper is to identify variables, based on evidence and literature, which are suitable for monitoring the impacts, multiple benefits and Ecosystem Services (ES) of NFM techniques, specifically; riparian vegetation and Runoff Attenuation Features (RAFs). The variables identified are translated in a conceptual tool which will enable data collection to support the quantification of NFM multiple benefits from an ES perspective. Essentially, the CMT, and the variables identified, will assist in addressing policy and research gaps whereby NFM measures must be appraised as a statutory obligation and multiple benefits are often not extensively researched, resulting in inconclusive scientific evidence of their wider impacts and benefits. This tool will adopt an "ecosystem service approach" in selecting variables, a relatively new concept and approach but one, advocated to provide a holistic technique able to represent the three pillars of sustainability (social, economic and environment).

**KEY WORDS:** Natural flood management, Multiple benefits, Ecosystem services, Riparian vegetation, Runoff attenuation features.

### 1 INTRODUCTION

Predictions by the Intergovernmental Panel on Climate Change (IPCC) indicate that the UK will experience increased summer temperatures and increased winter rainfall events that will become more intense (IPCC, 2007). Climate change is likely to increase the number of people at risk of being flooded from fluvial, pluvial and surface water sources. In order to mitigate the unwanted human, environmental and economic impacts of climate change, flooding must be managed cost-effectively and sustainably to ensure resilience and effective adaptation to future conditions. Natural Flood Management (NFM) is theorized and promoted to be a cost-effective sustainable measure for reducing flood risk; thus it is timely to explore this topic in the present study.

NFM has been formally introduced to the UK through the 2007 European (EU) Directive on the Assessment of Management of Flood Risk (2007/60/EC) (Floods Directive), which has been transposed into UK legislation in the form of the Flood Risk Management (Scotland) Act 2009 and the Flooding and Water Management Act 2010. These UK laws formally introduced the requirement for NFM techniques to be considered and appraised when managing flood risk. NFM is defined in Scotland as "*working with or restoring natural flooding processes with the aim of reducing flood risk and delivering other benefits*"(Flood Risk Management (Scotland) Act, 2009). There are numerous NFM techniques such as: agricultural land use practices; Riparian Vegetated Buffers (RVBs); afforestation; erosion control and sediment management; Runoff Attenuation Features (RAFs); drain blocking (agricultural and upland); bank stabilisation; re-meandering; wetlands; large woody debris; and floodplain restoration (reconnection, woodlands and wetlands).

Despite the statutory requirement for NFM to be considered when managing flood risk, policy has essentially promoted NFM prematurely, in that there is an inadequate body of evidence available yet to unequivocally conclude that natural processes and features can effectively reduce flood risk at various scales. It is widely indicated that catchment scale NFM effectiveness remains elusive and further extensive research in flood risk is required to inform policy. Further insufficient research has been applied to quantifying the multiple benefits of each NFM measure and given the statutory requirement to appraise shortlisted measures for a specific site only, limited data and tools exist to assist and support this process. NFM multiple benefits could be understood and evaluated by using an ecosystem service (ES) approach, enabling the benefits of each Thus, NFM measure to be examined in relation to the provision of ES (Frontier Economics Ltd et al., 2013, Iacob et al., 2012). ES are defined as dynamically complex interacting units at various scales which living organisms interact with one another chemically, physically or biologically, and with abiotic factors; creating natural processes that enable intricate ecological balances within one system (TEEB, 2012). These ecosystems and their processes provide goods and services that humans benefit from (and depend on) directly or indirectly: the concept of ecosystem goods and services is synonymous with ES (TEEB, 2012).

This paper proposes a tool for monitoring the effectiveness of NFM measures using an ES framework to identify the multiple benefits of each technique. For the purpose of this study, RVBs and RAFs will be assessed as they each represent opposite ends of the ES and NFM spectrum and therefore enable the management tool to be tested effectively. Riparian vegetation is derived as a water quality measure with extensive literature to indicate their ES provision and multiple benefits, but has recently been advocated as an NFM measure. Conversely, RAFs derived from a hard engineering background and have a good strong evidence base for their flood risk reduction abilities but limited scientific evidence on their multiple benefits or effects on ES.

## 2 STUDY METHODS

**Table 1** Management tool categories and definitions

| Tool Categories | Definitions of categories |
|---|---|
| Multiple benefits | The specific multiple benefits related to a specific NFM measure. |
| Variables | Measurable variables that can be monitored in the field to establish any changes that the NFM measure may have on its associated multiple benefits. |
| ES provided | Identifies the list of specific ES that are provided by the specific NFM measure. Colour coding of the variables shows the linkages between ES, variables and multiple benefits. |
| ES classification | Distinguishes the ES classification of corresponding multiple benefits and variables in relation to both the Millennium Ecosystem Assessment (MA) classification (supporting, regulating, provisioning and cultural) and the UK National Ecosystem Assessment (UKNEA) classification (primary/ intermediate, final and goods/ benefits). |

In order to identify the multiple benefits of RVBs and RAFs, the evidence gathered will highlight the potential variables that can be monitored in the field. Further to this review, the ES associated with these multiple benefits will be identified, as well as the evidence base for the ability of both NFM measures to reduce flood risk. Based on the findings of the review of literature a conceptual tool will be developed illustrating the linkages between NFM multiple benefits and ES. Prior to conducting the literature search, categories for the tool required categorising in order to determine how these would link together; the categories outlined in the framework are shown in Table 1.

## 3 RESULTS AND DISCUSSION

### 3.1 Riparian Vegetated Buffers Flood Risk Evidence

The RVB zone is an uncultivated strip of vegetated land adjacent to watercourses, which are considered an "ecotone" (defined as: a habitat where there is an abrupt meeting of two contrasting communities that are individually homogenous (Stockan et al., 2012, Pert et al., 2010)). RVBs vary from woodland species to grass and shrub species, all of which have an influence on surface and subsurface flows by creating storage, slowing flows and attenuating flood peaks (through hydraulic roughness): this influence varies with density, height, shape, physiology, flexibility, season and succession (Tabacchi et al., 2000). Key studies of flood risk reduction properties of RVBs include: Johnson *et* al. (2008) and Anderson *et al.* (2006). However, wider literature notably lacks monitoring based evidence that riparian vegetation (particularly non-woodland species) can reduce flood risk (Lane, 2008), which appears to be the research origin being from a water quality perspective rather than hydraulic flood risk perspective.

### 3.2 Riparian Vegetated Buffers Multiple Benefits

According to Stutter *et al*. (2012), RVBs and the crucial multiple functions they carry out are widely researched, but such literature is restricted to mostly single riparian functions. There is a need for science to address the interdisciplinary multiple function research gap (Stutter et al., 2012), made more pressing because the multiple benefits of RVBs need to be fully understood to ensure effective appraisal as a NFM measure or in terms of managing ES provision. As illustrated by Table 2, the benefits of RVBs can be categorized into: hydrology and hydraulics; ecology/ habitat/ biodiversity; pollution control; natural debris; riverbank stabilisation/ erosion control/ sediment trapping; and socio-economic.

### 3.3 Runoff Attenuation Feature Flood Risk Evidence

RAFs originate as a hard engineering solution to reducing flood risk that have essentially been naturalised, by using sustainable natural materials like wood and soil to become a viable NFM measure. They have also previously been utilised as a nutrient management feature to address diffuse pollution issues. RAFs are commonly implemented as an "off-line" flood storage feature aimed to attenuate out-of-bank flows during flood events or overland flow (Environment Agency, 2012). According to a study by Wilkinson *et al*. (2010b) in the Belford catchment (UK), RAFs demonstrated their effectiveness by becoming functional in the first flush of a flood, then slowly releasing the water back to the stream without adversely affecting the receding limb (Wilkinson et al., 2010b). Associated travel time to peak of the flood showed a delay by 15 minutes following RAF construction (Wilkinson et al., 2010b). Wilkinson *et al.* (2010b) therefore demonstrates the effectiveness and potential to reduce local scale, and catchment scale (Nicholson et al., 2012), flood risk by using RAFs.

### 3.4 Runoff Attenuation Feature Multiple Benefits

Table 3 outlines the multiple benefits of RAFs: hydraulics/ hydrology; ecology/ habitat/ biodiversity; pollution control/ sediment trapping; and socio-economic. Barber and Quinn (2012a) recommend further research and development of a methodology to adequately quantify the multiple benefits of RAFs from an ES perspective. This paper aims to address this research gap through the formalisation of a conceptual tool to identify variables for an effective monitoring strategy that can quantify multiple benefits and ES.

**Table 4** Riparian vegetated buffers multiple benefits and measurable variables.

| BENEFIT CATEGORY | SPECIFIC RIPARIAN BENEFITS | VARIABLES | | LITERATURE |
|---|---|---|---|---|
| **Hydraulics/ Hydrology** | • Hydrological functions: interception, stem flow, infiltration, evapotranspiration, water storage and floodplain connection<br>• Hydraulic roughness, turbulence, flood peak reduction<br>• Flood risk reduction (e.g. for a 1yr RP- 15% increase in storage and Tp reduced by 30 minutes) | - Canopy density<br>- Species physiology<br>- Vol. rainfall/ time<br>- Evapotranspiration rates<br>- Rainfall/ runoff<br>- Soil moisture<br>- Slope (channel and hill)<br>- Geology<br>- Temp. (soil, water, air)<br>- Particle size distribution (PSD) of sediment load (bed and suspended)<br>- Root system<br>- Distance from stream<br>- Soil infiltration rate/ compaction | - Soil structure, type and distribution<br>- Vol. of biomass<br>- Groundwater level<br>- Time to peak<br>- Base flow<br>- Peak/ stage/ bank full discharge<br>- Manning's *n* coefficient<br>- Channel geometry<br>- Overbank area wetted by flood<br>- Land use<br>- Stocking densities<br>- Crop species, cultivation practices and timeframes | (Broadmeadow and Nisbet 2004, Pollen-Bankhead and Simon 2010, Rassam et al. 2006, Anderson et al. 2006, Gribovszki et al. 2008, Anderson et al. 2005, Merritt et al. 2009, Tabacchi et al. 2000, Ranalli and Macalady 2010, Johnson et al. 2008) |
| **Ecology/ Habitat/ Biodiversity** | • Food source: e.g. inverts<br>• Stream shading & micro-climates<br>• Ecological connectivity<br>• Species diversity (in dominantly homogenous landscapes)<br>• Habitat for various aquatic and terrestrial species | - Vegetation/ canopy height<br>- Canopy cover<br>- Vegetation density (% bare ground)<br>- Soil chemistry (pH, N, P, C, S, K, Ma, Ca & Si)<br>- Species richness and abundance of aquatic and terrestrial invertebrates<br>- Buffer strip age | - Classification of habitat (according to phase 1 habitat survey)<br>- Land use<br>- Fish- population, age structure, number caught in a recreational fishing season<br>- Spatial differences in water temperature | (Tabacchi et al. 2000, Stutter et al. 2012, Mander et al. 2005, Stockan et al. 2012, Gribovszki et al. 2008) |
| **Natural Debris** | • Increase and decrease in flood risk<br>• Attenuate flood peaks<br>• Source and sink for organic and inorganic debris<br>• Increased N uptake by autotrophs (in pools)<br>• Hydraulic roughness | - Manning's *n* coefficient<br>- N- (water and sediment)<br>- Water velocity<br>- Groundwater level<br>- Time to peak<br>- Base flow<br>- Peak/ stage/ bank full discharge | - Channel geometry & slope (channel and hill)<br>- Rainfall/ runoff<br>- Vol. rainfall/time<br>- Evapotranspiration rates<br>- Land use<br>- Overbank area wetted by flood | (Broadmeadow and Nisbet 2004, Tabacchi et al. 2000, Piégay and Gurnell 1997, Stutter et al. 2012, Weigelhofer et al. 2012) |

| BENEFIT CATEGORY | SPECIFIC RIPARIAN BENEFITS | VARIABLES | | LITERATURE |
|---|---|---|---|---|
| **Pollution Control** | • Nutrient Cycling: N, P, C, S & pathogens<br>• Maintain DO levels<br>• Filtration of diffuse pollution, heavy metals & contaminants (pesticides/ herbicides)<br>• Improve water quality<br>• Reduce sedimentation in channel- reduced flood risk, turbidity and mobilisation of P, N and pathogens.<br>• Intercept pollution runoff from land uses | **In addition to Hydraulics/ Hydrology variables (above):**<br>- P- total, particulate and dissolved (soil, sediment & water)<br>- N- total, organic and dissolved (soil, sediment & water)<br>- Heavy metals and contaminants<br>- Fish- population, age structure, number caught in a recreational fishing season | - Suspended solids (SS)<br>- Sediment settling velocity<br>- PSD of bed and suspended sediment<br>- Coliform bacteria<br>- Soil organic carbon (SOC)<br>- Dissolved organic carbon (DOC)<br>- Oxygen concentrations<br>- Water velocity | (Stutter et al. 2012, Stutter and Richards 2012, Roberts et al. 2012, Dorioz et al. 2006, Hoffmann et al. 2009, Stutter et al. 2009, Merritt et al. 2009, Collins et al. 2009, Rassam et al. 2006, Krovang et al. 2012, Mander et al. 2005, Ranalli and Macalady 2010) |
| **Riverbank Stabilisation/**<br><br>**Erosion Control/**<br><br>**Sediment Trapping** | - Reduces bank erosion<br>- Reduces sedimentation of channel and therefore reduces flood risk, turbidity and mobilisation of P, N and pathogens<br>- Effects geomorphological processes and formations (meanders/ channel shape/ bars)<br>- Improves denitrification (more organic matter (carbon) in saturated areas)<br>- Improves water quality- reduces turbidity, P and N<br>- Improves soil formation, plant growth and plant nutrient uptake<br>- Improves fish habitat | **In addition to Hydraulics/ Hydrology and Pollution Control variables:**<br>- Cross-sectional change<br>- In-stream bedforms<br>- Sinuosity<br>- River migration rates<br>- Bank material<br>- Soil formation rate | - Macrophytes: population, distribution and density.<br>- Vol. biomass<br>- Coliform bacteria<br>- Soil organic carbon (SOC)<br>- Dissolved organic carbon (DOC)<br>- Oxygen concentrations | (Stutter et al. 2009, Broadmeadow and Nisbet 2004, Collins et al. 2010, Pollen-Bankhead and Simon 2010, Krovang et al. 2012, Merritt et al. 2009, Roberts et al. 2012, Dorioz et al. 2006, Stutter and Richards 2012, Stutter et al. 2012, Mander et al. 2005) |
| **Socio-Economic** | • Aesthetically pleasing<br>• Public/ Educational/ recreational access<br>• Biomass/ food/ fuel | - Financial returns (biomass)<br>- Fish- population, age structure, number caught in a recreational fishing season | - No. of fishing permits sold per season/ no. visitors<br>- Savings (water treatment/water quality | (Lovett et al. 2004, Stutter et al. 2012, Pert et al. 2010) |

**Table 5** Runoff attenuation feature multiple benefits and measurable variables

| BENEFIT CATEGORY | SPECIFIC RAF BENEFITS | VARIABLES | | LITERATURE |
|---|---|---|---|---|
| **Hydraulics/ Hydrology** | • Water storage<br>• Groundwater recharge<br>• Disconnection, interception and attenuation of overland and out-of-bank flows<br>• Slow infiltration of stored water- attenuating peak flows.<br>• Flood risk reduction properties | - Vol. of water storage capacity<br>- Time to peak<br>- Peak/ stage/ bank full discharge<br>- Manning's *n* co-efficient<br>- Slope (channel and hill slope-DTM or LiDAR)<br>- Soil type & structure<br>- Geology<br>- Residence time (in RAF)<br>- Vol. rainfall/ time | - Soil infiltration rate & compaction<br>- Channel geometry<br>- Overbank area wetted by flood<br>- Rate of sediment build up behind RAF<br>- Land use<br>- Soil moisture/ groundwater level<br>- Temp. (water)<br>- Evaporation rate (diurnal and seasonal)<br>- Hydrological pathways (seasonal)<br>- Drainage & irrigation connectivity | (Frontier Economics Ltd et al. 2013, N Barber, J and P. F Quinn 2012, Nicholson et al. 2012, Owen et al. 2012, Wilkinson et al. 2010b, Wilkinson et al. 2010a) |
| **Ecology/ Habitat/ Biodiversity** | • Habitat creation & protection (fish)<br>• Landscape heterogeneity<br>• Biodiversity | - Fish species dynamics: age structure, presence and population | - Number of fish caught (recreationally)<br>- Sightings of migratory birds<br>- Population of migratory birds | (N Barber, J and P. F Quinn 2012, Morris et al. 2008, Jonczyk et al. 2008) |
| **Pollution Control**<br><br>**Sediment Trapping** | • Nutrient cycling- N, P, C, S & pathogens (denitrification & carbon sequestration)<br>• Filtration of diffuse pollution, heavy metals & contaminants (fertilisers/ pesticides/ herbicides/ pathogens)<br>• Mitigates periodic nutrient release incidents<br>• Improved water quality (likely) | - Soil type/structure/ profile/ distribution/ nutrient retention capacity<br>- Soil moisture & chemistry ($NH_4$-N, $NO_3$-N, $PO_4$-P, pH, N, P, C, K, Ma, Si, S and Ca)<br>- Land use & stock density<br>- nutrient sources- proximity and connectivity<br>- Hydrological pathways | - Crop species & cultivation practices<br>- Organic matter<br>- N and P export coefficient rates from land use<br>- N and P annual excretion and defecation rates from livestock<br>- Fertiliser/ pesticides/ herbicide application- type, volumes, concentrations, spatial extent, timing of application<br>- Temp. (water and soil)<br>- Macroinvertebrate indicator species | (Frontier Economics Ltd et al. 2013, N. J Barber and P. F Quinn 2012, Fink and Mitsch 2004, Fisher and Acreman 2004, Jonczyk et al. 2008, Nicholson et al. 2012) |
| **Socio-Economic** | • Aesthetic appeal<br>• Re-use of sediment<br>• Reduce costs of the impact of flooding on local communities. | - Equivalent cost of fertiliser for sediment re-use<br>- Cost of flood impacts (when they occur) | - Number of properties at flood risk<br>- Cost of flood insurance<br>- Equivalent savings on water treatment due to improved water quality | No relevant literature |

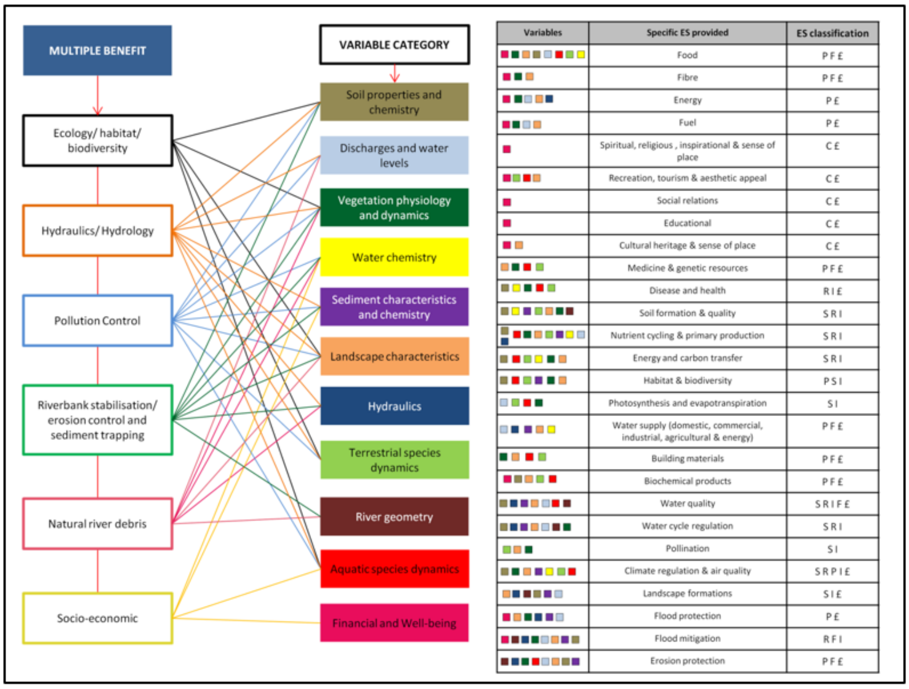


**Figure 1** RVB conceptual NFM-Multiple Benefits-ES management tool. 'S'- supporting services, 'R' regulating services, 'P' provisioning services, 'C' cultural services, 'I' primary/ intermediate services, 'F' final services, '£' goods and benefits.

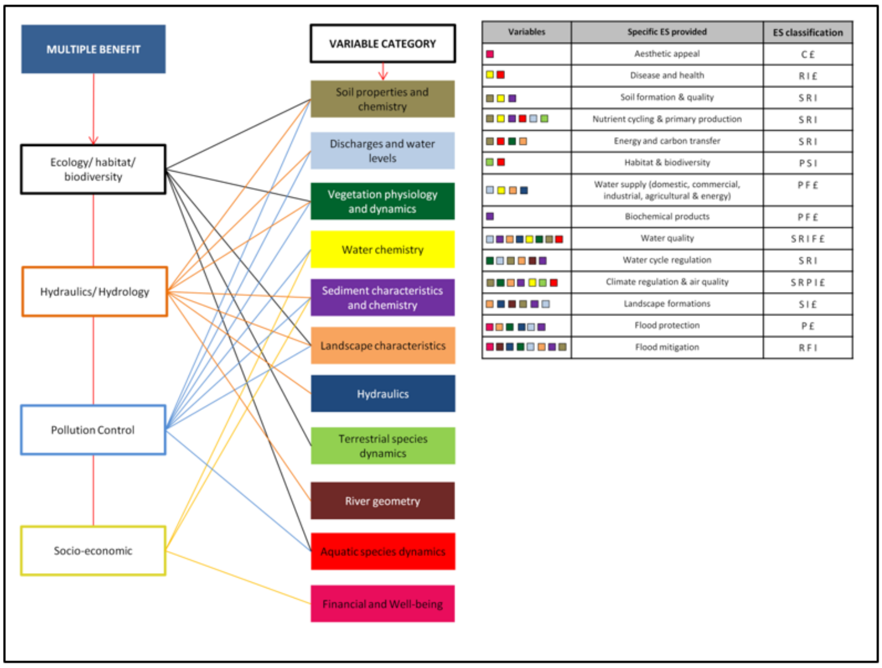


**Figure 2** RAF conceptual NFM-Multiple Benefits-ES management tool. 'S'- supporting services, 'R' regulating services, 'P' provisioning services, 'C' cultural services, 'I' primary/ intermediate services, 'F' final services, '£' goods and benefits

### 3.5 Discussion

The review of literature indicates there is a larger evidence base for RVBs in relation to their ability to deliver ES compared to that of RAFs, although, most literature does not explicitly look at "ecosystem services" but rather the individual benefits it affords (Stutter et al., 2012). There is a notable lack of evidence to suggest that RVBs can reduce flood risk; most studies model their impact rather than using empirical data. Conversely, RAFs do have some literature to support flood risk reduction based on both empirical and modelling studies, yet there is an obvious gap in research for RAF multiple benefits (Stockan et al., 2012). Comparing Figure 1 and 2 highlights several key points to consider:

- RVBs have more multiple benefits than RAFs
- The multiple benefits of both techniques cover all the ES classifications
- The performance of NFM techniques can be monitored from the perspective of multiple benefits or ES, which dictates the variables chosen for any study (as does cost and time restrictions)
- Coverage of variables chosen for monitoring are dictated by the range and quantity of ES or multiple benefits that are desired
- The tool highlights which variables relate to which multiple benefits or ES chosen, and can be used as a reference for converting between approaches

This highlights the extent of the complexity in considering NFM and its multiple benefits from an ES perspective. The tool and tables are, to date, relatively biased towards assessing only multiple benefits and excluding of a mechanism for additionally (or scoring) the NFM measure's ability to reduce food risk. In relation to Section 20 of the Flood Risk Management (Scotland) Act 2009, there is a need to appraise the "timescale to effectiveness" of any measure. Consequently, further research is required to apply this conceptual tool to all NFM measures, as well as integrate and account for timescales, spatial scales and flood risk effectiveness. Until these can be addressed the tool does not yet fully evaluate NFM multiple benefits from an ES perspective.

## 4 CONLUSIONS

In conclusion, UK flood risk policy and practitioners require more evidence that NFM can effectively reduce flood risk at various scales. Moreover, quantification of NFM multiple benefits are urgently needed to enable statutory appraisals of NFM. The push towards an ES approach to catchment management in the UK is driving the need to understand the overlaps and connections between multiple benefits and ES. This conceptual management tool sets out the numerous field monitoring variables and how they can be analysed to quantify the impact of a specific NFM measure in these terms, thereby identifying similarities and connections between types. This tool is however, is in its infancy and requires further development to integrate key elements such as: timescales, spatial scales and flood risk mitigation effectiveness.

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## Appendix 2

### Definition and values for monthly weather statistics required by SWAT model

Aboyne monthly weather statistics (1994 – 2016) required by SWAT model and their definition.

| *Statistic* | *Description* | *Jan* | *Feb* | *Mar* | *Apr* | *May* | *Jun* | *Jul* | *Aug* | *Sep* | *Oct* | *Nov* | *Dec* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **PCPSKW** | Skewness for daily precipitation (mm/day) | 4.389 | 4.506 | 3.751 | 3.706 | 4.489 | 4.736 | 2.941 | 4.022 | 6.359 | 3.706 | 3.541 | 3.693 |
| **PCPSTD** | Standard deviation for daily precipitation (mm/day) | 5.160 | 3.493 | 2.985 | 4.188 | 4.098 | 4.575 | 4.838 | 4.740 | 5.586 | 6.232 | 5.078 | 4.565 |
| **PCPMM** | Average precipitation (mm/day) | 2.39 | 1.67 | 1.50 | 1.99 | 1.89 | 2.07 | 2.51 | 2.26 | 1.94 | 2.98 | 2.75 | 2.31 |
| **PCPD** | Average number days of precipitation (given by the number of wet days in a month divided by the number of years) | 0.915 | 0.777 | 0.771 | 0.752 | 0.784 | 0.739 | 0.737 | 0.803 | 0.718 | 0.915 | 0.917 | 0.941 |
| **PR_W1** | Probability of wet day following dry day (given by the number of wet days following a dry day in a month divided by the total number of dry days in month.) | 0.633 | 0.581 | 0.448 | 0.483 | 0.472 | 0.476 | 0.478 | 0.468 | 0.524 | 0.535 | 0.655 | 0.641 |
| **PR_W2** | Probability of wet day following wet day (given by the number of wet days following a wet day in a month divided by the total number of wet days in a month) | 0.706 | 0.682 | 0.673 | 0.651 | 0.678 | 0.654 | 0.638 | 0.689 | 0.604 | 0.727 | 0.747 | 0.737 |
| **RAINHHMX** | Maximum 0.5hr rainfall for all period of rainfall (mm) (is the maximum 0.5hr rainfall for whole period of data. As the minimum time step of existing rainfall data is hourly, this was calculated by dividing the maximum 1hr rainfall for whole period by 2) | 2.05 | 1.35 | 1.30 | 1.81 | 2.32 | 2.99 | 3.01 | 3.05 | 2.60 | 2.40 | 2.06 | 1.95 |
| **TMPMN** | Average minimum air temperature (°C) | -0.2 | -0.3 | 0.6 | 2.0 | 4.0 | 7.5 | 9.3 | 8.8 | 7.0 | 4.4 | 1.8 | -0.3 |

| *Statistic* | *Description* | *Jan* | *Feb* | *Mar* | *Apr* | *May* | *Jun* | *Jul* | *Aug* | *Sep* | *Oct* | *Nov* | *Dec* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **TMPMX** | Average maximum air temperature (°C) | 5.9 | 6.5 | 8.7 | 11.2 | 14.0 | 16.4 | 18.6 | 18.3 | 16.2 | 12.3 | 8.7 | 5.8 |
| **TMPSTDMN** | Standard deviation of minimum air temperature | 3.7 | 3.7 | 3.5 | 3.3 | 3.3 | 2.8 | 2.8 | 3.1 | 3.4 | 3.6 | 3.9 | 3.9 |
| **TMPSTDMX** | Standard deviation of maximum air temperature | 3.1 | 3.0 | 3.2 | 3.3 | 3.5 | 3.3 | 3.1 | 2.8 | 2.8 | 2.7 | 3.0 | 3.5 |
| **SOLARAV** | Average daily solar radiation ($MJ/m^2/day$) | 1.54 | 3.43 | 6.48 | 10.74 | 14.41 | 13.81 | 13.81 | 10.93 | 7.05 | 3.48 | 1.74 | 1.10 |
| **DEWPT** | Average dew point (°C) | 0.35 | 0.15 | 0.90 | 2.58 | 4.76 | 8.67 | 10.28 | 9.92 | 8.22 | 5.63 | 2.88 | 0.75 |
| **WINDAV** | Average wind speed (m/s) | 3.683 | 3.838 | 3.777 | 3.222 | 3.071 | 2.922 | 2.601 | 2.544 | 2.801 | 3.061 | 3.191 | 3.453 |

**Appendix 3**

Crop Range – Land Use input data required

Crop growth indices and land use values used for SWAT code variables allocated to LCM2007 land covers. Curve numbers (CN2) and Manning's n (OV_N) are highlighted in green.

| | | | | CROP NAME | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| ***CODE*** | ***MIN*** | ***MAX*** | ***DEFINITION*** | ***AGRL*** | ***FRSD*** | ***FRSE*** | ***RNGB*** | ***RNGE*** | ***WPAS*** |
| ***OV_N*** | 0.01 | 30 | Manning's "n" value for overland flow. | 0.14 | 0.25 | 0.25 | 0.15 | 0.15 | 0.15 |
| ***CN2A*** | 25 | 98 | SCS runoff curve number for moisture condition II. | 67 | 45 | 25 | 39 | 49 | 49 |
| ***CN2B*** | 25 | 98 | SCS runoff curve number for moisture condition II. | 77 | 66 | 55 | 61 | 69 | 69 |
| ***CN2C*** | 25 | 98 | SCS runoff curve number for moisture condition II. | 83 | 77 | 70 | 74 | 79 | 79 |
| ***CN2D*** | 25 | 98 | SCS runoff curve number for moisture condition II. | 87 | 83 | 77 | 80 | 84 | 84 |
| ***IDC*** | 1 | 7 | Land Cover/Plant Classification. | 4 | 7 | 7 | 6 | 6 | 6 |
| ***CROPNAME*** | 10 | 90 | (Full name for) four character code to represent the land cover/plant name. | Agricultural Land-Generic | Forest-Deciduous | Forest-Evergreen | Range-Brush | Range-Grasses | Winter Pasture |
| ***BIO_E*** | 10 | 90 | Biomass/Energy Ratio. | 33.5 | 15 | 15 | 34 | 34 | 30 |
| ***HVSTI*** | 0.01 | 1.25 | Harvest index. | 0.45 | 0.76 | 0.76 | 0.9 | 0.9 | 0.9 |
| ***BLAI*** | 0.5 | 10 | Max leaf area index. | 3 | 5 | 5 | 2 | 2.5 | 4 |
| ***FRGRW1*** | 0 | 1 | Fraction of the plant growing season corresponding to the 1st. Point on the optimal leaf area development curve. | 0.15 | 0.05 | 0.15 | 0.05 | 0.05 | 0.15 |
| ***LAIMX1*** | 0 | 1 | Fraction of the max. leaf area index corresponding to the 1st. point on the optimal leaf area development curve. | 0.05 | 0.05 | 0.7 | 0.1 | 0.1 | 0.01 |
| ***FRGRW2*** | 0 | 1 | Fraction of the plant growing season corresponding to the 2nd. point on the optimal leaf area development curve. | 0.5 | 0.4 | 0.25 | 0.25 | 0.25 | 0.5 |

| CODE | MIN | MAX | DEFINITION | CROP NAME | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | ***AGRL*** | ***FRSD*** | ***FRSE*** | ***RNGB*** | ***RNGE*** | ***WPAS*** |
| ***LAIMX2*** | 0 | 1 | Fraction of the max. leaf area index corresponding to the 2nd. point on the optimal leaf area development curve. | 0.95 | 0.95 | 0.99 | 0.7 | 0.7 | 0.95 |
| ***DLAI*** | 0.15 | 1 | Fraction of growing season when leaf area starts declining. | 0.64 | 0.99 | 0.99 | 0.35 | 0.35 | 0.8 |
| ***CHTMX*** | 0.1 | 20 | Max canopy height. | 1 | 6 | 10 | 1 | 1 | 1.5 |
| ***RDMX*** | 0 | 3 | Max root depth. | 2 | 3.5 | 3.5 | 2 | 2 | 2 |
| ***T_OPT*** | 11 | 38 | Optimal temp for plant growth. | 30 | 30 | 30 | 25 | 25 | 15 |
| ***T_BASE*** | 0 | 18 | Min temp plant growth. | 11 | 10 | 0 | 12 | 12 | 0 |
| ***CNYLD*** | 0.0015 | 0.075 | Fraction of nitrogen in seed. | 0.0199 | 0.0015 | 0.0015 | 0.016 | 0.016 | 0.0234 |
| ***CPYLD*** | 0.0001 | 0.015 | Fraction of phosphorus in seed. | 0.0032 | 0.0003 | 0.0003 | 0.0022 | 0.0022 | 0.0033 |
| ***BN1*** | 0.004 | 0.07 | Fraction of N in plant at emergence. | 0.044 | 0.006 | 0.006 | 0.02 | 0.02 | 0.056 |
| ***BN2*** | 0.002 | 0.05 | Fraction of N in plant at 0.5 maturity. | 0.0164 | 0.002 | 0.002 | 0.012 | 0.012 | 0.021 |
| ***BN3*** | 0.001 | 0.27 | Fraction of N in plant at maturity. | 0.0128 | 0.0015 | 0.0015 | 0.005 | 0.005 | 0.012 |
| ***BP1*** | 0.0005 | 0.01 | Fraction of P at emergence. | 0.006 | 0.0007 | 0.0007 | 0.0014 | 0.0014 | 0.0099 |
| ***BP2*** | 0.0002 | 0.007 | Fraction of P at 0.5 maturity. | 0.0022 | 0.0004 | 0.0004 | 0.001 | 0.001 | 0.0022 |
| ***BP3*** | 0.0003 | 0.0035 | Fraction of P at maturity. | 0.0018 | 0.0003 | 0.0003 | 0.0007 | 0.0007 | 0.0019 |
| ***WSYF*** | -0.2 | 1.1 | Lower limit of harvest index. | 0.25 | 0.01 | 0.6 | 0.9 | 0.9 | 0.9 |
| ***USLE_C*** | 0.001 | 0.5 | Min value of USLE C factor applicable to the land cover/plant. | 0.2 | 0.001 | 0.001 | 0.003 | 0.003 | 0.003 |
| ***GSI*** | 0 | 5 | Max stomatal conductance (in drought condition). | 0.005 | 0.002 | 0.002 | 0.005 | 0.005 | 0.005 |
| ***VPDFR*** | 1.5 | 6 | Vapor pressure deficit corresponding to the fraction maximum stomatal conductance defined by FRGMAX | 4 | 4 | 4 | 4 | 4 | 4 |
| ***FRGMAX*** | 0 | 1 | Fraction of maximum stomatal conductance that is achievable at a high vapor pressure deficit. | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 |
| ***WAVP*** | 0 | 50 | Rate of decline in radiation use efficiency per unit increase in vapor pressure deficit. | 8.5 | 8 | 8 | 10 | 10 | 8 |

| | | | | CROP NAME | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| ***CODE*** | ***MIN*** | ***MAX*** | ***DEFINITION*** | ***AGRL*** | ***FRSD*** | ***FRSE*** | ***RNGB*** | ***RNGE*** | ***WPAS*** |
| ***CO2HI*** | 300 | 1000 | Elevated CO2 atmospheric concentration. | 660 | 660 | 660 | 660 | 660 | 660 |
| ***ALAI_MIN*** | 0 | 0.99 | Minimum leaf area index for plant during dormant period | 0 | 0.75 | 0.75 | 0 | 0 | 0 |
| ***BIO_LEAF*** | 0 | 1 | Fraction of tree biomass converted to residue during dormancy | 0 | 0.3 | 0.3 | 0 | 0 | 0 |
| ***MAT_YRS*** | 0 | 100 | Number of years required for tree species to reach full development | 0 | 10 | 30 | 0 | 0 | 0 |
| ***BMX_TREES*** | 0 | 5000 | Maximum biomass for a forest | 0 | 1000 | 1000 | 0 | 0 | 0 |
| ***EXT_COEF*** | 0 | 2 | Light extinction coefficient | 0.65 | 0.65 | 0.65 | 0.33 | 0.33 | 0.65 |
| ***BM_DIEOFF*** | 0 | 1 | Biomass die-off fraction | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |

**Appendix 4**

IDC definitions- SWAT land cover/plant description differentiation

| *IDC* | *Land cover/plant description* | *Key Differences* |
|---|---|---|
| *1* | Warm season annual legume | Simulate nitrogen fixation |
| | | Root depth varies during growing season due to root growth |
| *2* | Cool season annual legume | Simulate nitrogen fixation |
| | | Root depth varies during growing season due to root growth |
| | | Fall-planted land covers will go dormant when day length is less than the threshold day length |
| *3* | Perennial legume | Simulate nitrogen fixation |
| | | Root depth always equal to the maximum allowed for the plant species and soil |
| | | Plant goes dormant when day length is less than the threshold day length |
| *4* | Warm season annual | Root depth varies during growing season due to root growth |
| *5* | Cool season annual | Root depth varies during growing season due to root growth |
| | | Fall-planted land covers will go dormant when day length is less than the threshold day length |
| *6* | Perennial | Root depth always equal to the maximum allowed for the plant species and soil |
| | | Plant goes dormant when day length is less than the threshold day length |
| *7* | Trees | Root depth always equal to the maximum allowed for the plant species and soil |
| | | Plant goes dormant when day length is less than the threshold day length |
| | | Partitions new growth between leaves/needles and woody growth |
| | | Growth in given year will vary depending on the age of the tree relative to the number of years required for the tree to full development/maturity |
| | | Plant goes dormant when the day length is less than the threshold day length |

## Appendix 5

SWAT model's required soil properties, their definition and derivation from Hydrology of Soil Types (HOST) data (JHI, 2014).

| SWAT LABEL | MIN | MAX | DEFAULT | UNIT | SWAT DEFINITION | JHI DERIVATION FROM HOST SOIL DATASET |
|---|---|---|---|---|---|---|
| **NLAYERS** | 1 | 10 | -999 | na | Number of layers in the soil. | |
| **HYDGRP** | 0 | 0 | -999 | na | Soil Hydrologic Group | Derived from HOST class and associated SPR by soil scientist Dr. Allan Lilly (JHI, 2014) |
| **SOL_ZMX** | 0 | 3500 | -999 | [mm] | Maximum rooting depth of soil profile | Top & bottom of the soil layer (cm converted to mm) (HORZ_TOP and HORZ_BOTTOM) |
| **ANION_EXCL** | 0.01 | 1 | 0.5 | [fraction] | Fraction of porosity (void space) from which anions are excluded | Default used as no JHI data existed to provide true representations |
| **SOL_CRK** | 0 | 1 | 0.5 | [fraction] | Crack volume potential of soil | Default used as no JHI data existed to provide true representations |
| **TEXTURE** | 0 | 0 | -999 | na | Texture of soil layer | Texture class (TEXTURE_BSTC) |
| **SOL_Z** | 0 | 3500 | -999 | [mm] | Depth from soil surface to bottom of layer | Top & bottom of the soil layer (cm converted to mm) (HORZ_TOP and HORZ_BOTTOM) |
| **SOL_BD** | 0 | 2.5 | -999 | [$g/cm^3$] | Moist bulk density | Predicted bulk density (g/cm3) (DBD_PRED) |
| **SOL_AWC** | 0 | 1 | -999 | [mm/mm] | Available water capacity of the soil layer | Field capacity – permanent wilting point (THETA_300 – THETA_15000) |
| **SOL_K** | 0 | 2000 | -999 | [mm/hr] | Saturated hydraulic conductivity | Saturated hydraulic conductivity predicted using the HYPRES suite of pedotransfer functions (cm/day converted to mm/hr) |
| **SOL_CBN** | 0 | 53 | -999 | [%] | Organic carbon content | Median carbon content (percentage by weight) (CARBON_MEDIAN) |
| **CLAY** | 0 | 100 | -999 | [%] | Clay content | Median clay content (<2 micron fraction) as percentage (CLAY_MEDIAN) |

| | | | | | | |
|---|---|---|---|---|---|---|
| **SILT** | 0 | 100 | -999 | [%] | Silt content | Median silt content (2-50 microms) as percentage (SILT_MEDIAN) |
| **SAND** | 0 | 100 | -999 | [%] | Sand content | Median sand content (50-2000 microns) as percentage (CALC_SAND_MEDIAN) |
| **ROCK** | 0 | 100 | -999 | [%] | Rock fragment content | Estimated stone content as percentage (STONES_EST) |
| **SOL_ALB** | 0 | 0.25 | -999 | na | Moist soil albedo | Default used as no JHI data existed to provide true representations |
| **USLE_K** | 0 | 0.65 | -999 | na | USLE equation soil erodibility (K) factor | Default used as no JHI data existed to provide true representations |

**Appendix 6**

Tarland soil series HOST classification values used and the relevant SWAT Hydrological Group (HYDGRP)

Soil properties data were provided for each soil series for both cultivated (CULT) and semi-natural conditions (SEMI). Each soil series and its allocated CULT or SEMI values based on the most dominant type of cover in the catchment. Where CULT land use was dominant for a soil series but only SEMI data existed, the SEMI data would be used, and vice-versa, to limit the use if SWAT default values. However, default values were applied to fraction of porosity (void space) from which anions are excluded (ANION_EXCL), crack volume potential of soil (SOL_CRK), moist soil albedo (SOL_ALB), and soil erodibility factor (USLE_K)**.** HOST classifications are listed**,** including standard percentage runoff (SPR), for each soil series and identifies the hydrological group (HYDGRP) allocated by Lilly (2014).

| ***SOIL SERIES*** | ***SOIL TYPE*** | ***RANK 1 LAND USE*** | ***RANK 2 LAND USE*** | ***CULT/SEMI VALUES*** | ***N0. LAYERS*** | ***HOST CLASS*** | ***HOST SPR*** | ***HYDGRP*** |
|---|---|---|---|---|---|---|---|---|
| *ANNISTON* | Humus-iron podzols | Improved | Arable | CULT | 4 | 13 | 2 | B |
| *BASINPEAT* | Dystrophic basin peat | Rough low production grassland | Improved | CULT (limited SEMI data) | 3 | 12 | 60 | D |
| *BOYNDIE* | Humus-iron podzols | Improved | Arable | CULT | 4 | 5 | 14.5 | A |
| *BRUNTLAND* | Humus-iron podzols | Heather grass | Coniferous | SEMI | 6 | 17 | 29.2 | B |
| *CHARR* | Peaty podzols | Coniferous | Heather shrub | SEMI | 6 | 15 | 48.4 | C |
| *CORBY* | Humus-iron podzols | Improved | Coniferous | CULT | 4 | 5 | 14.5 | A |
| *COUNTESSWELLS* | Humus-iron podzols | Coniferous | Improved | SEMI | 6 | 17 | 29.2 | B |
| *COUNTSKEL* | No data | Coniferous | None | SEMI | 3 | 22 | 60 | D |
| *DALLACHY* | Noncalcareous gleys | Improved | Heather grass | CULT | 3 | 14 | 25.3 | B |
| *DESS* | Humus-iron podzols | Improved | Arable | CULT | 4 | 18 | 47.2 | C |
| *DINNET* | Brown earths | Improved | Arable | SEMI (no CULT data) | 4 | 17 | 29.2 | B |
| *DRUMLASIE* | Peaty gleys | Rough low production grassland | Improved | SEMI (no CULT data) | 5 | 15 | 48.4 | C |

| SOIL SERIES | SOIL TYPE | RANK 1 LAND USE | RANK 2 LAND USE | CULT/SEMI VALUES | N0. LAYERS | HOST CLASS | HOST SPR | HYDGRP |
|---|---|---|---|---|---|---|---|---|
| *FERRAR* | Noncalcareous gleys | Heather grass | Deciduous | SEMI | 4 | 14 | 25.3 | B |
| *INSCH* | Brown earths | Arable | Improved | CULT | 4 | 17 | 29.2 | B |
| *INVERNETTIE* | Brown earths | Acid grassland | Deciduous | SEMI | 4 | 13 | 2 | B |
| *MARYFIELD* | Iron podzols | Improved | Coniferous | SEMI (no CULT data) | 5 | 13 | 2 | B |
| *MIXED BOTTOM LAND (MOBOL)* | Alluvium: undifferentiated | Improved | Arable | CULT | 3 | 10 | 25.3 | A |
| *MUNDURNO* | Peaty gleys | Improved | Rough low production grassland | CULT | 4 | 12 | 60 | D |
| *MYRETON* | Noncalcareous gleys | Coniferous | Acid grassland | SEMI | 4 | 24 | 39.7 | C |
| *OLDTOWN* | Iron podzols | Coniferous | Arable | SEMI | 4 | 5 | 14.5 | A |
| *PITMEDDEN* | Noncalcareous gleys | Improved | Arable | CULT | 4 | 24 | 39.7 | C |
| *PRESSENDYE* | Peaty podzols | Heather shrub | Heather grass | SEMI | 5 | 15 | 48.4 | C |
| *TARVES* | Brown earths | Improved | Arable | CULT | 5 | 17 | 29.2 | B |
| *TERRYVALE* | Noncalcareous gleys | Rough low production grassland | Improved | CULT | 4 | 14 | 25.3 | B |
| *THISTLYHILL* | Brown earths | Improved | Arable | CULT | 4 | 13 | 2 | B |
| *TILLYPRONIE* | Humus-iron podzols | Coniferous | Heather grass | SEMI | 5 | 17 | 29.2 | B |
| *UNDIFFERENTIATED ALLUVIAUM (UNIFALLUVIAL)* | Alluvium: undifferentiated | Improved | Arable | CULT | 3 | 10 | 25.3 | A |

**Appendix 7**

**SWAT-CUP background**

SWAT-CUP utilises the outputs from SWAT and performs a semi-automatic calibration. The Sequential Uncertainty Fitting (SUFI-2) approach used in SWAT-CUP was applied to the calibration of the Tarland SWAT (daily resolution) and is a stochastic method which enables users to identify the uncertainties (as the 95% probability, explained below).

The stochastic approach recognises a range of parameter values that make the 'best simulation' rather than determining single values for the calibrated parameters (Abbaspour, 2015). The 'best simulation' does have a single value applied but outlines the ranges in which each parameter value may be applied within its uncertainty range. The uncertainty is shown for output variables (flow for this study) as 95% probability distributions using the Latin hypercube sample method known as the 95PPU in SWAT-CUP outputs (Abbaspour, 2015). This 95PPU is shown as an upper and lower uncertainty bracket for flow: the observed values should fall within this uncertainty bracket, which should be a small as possible. If the observed data fall within this 95PPU bracket it is assumed the model can depict the catchment processes. The caveat however, is that different parameter sets produce similar results (Abbaspour, 2015), also known as equifinality (Beven and Freer, 2001a).

Additional key statistics used are P-factor and R-factor. These statistics assist in determining the goodness of fit between simulations and observations. The 95PPU, P-factor and R-factor are essential in the calibration process in conjunction with other objective statistics outlined below.

Table 7.A. SWAT-CUP statistics used to assess goodness of fit (definitions and values from Abbaspour et al., 2015).

| ***Statistic*** | ***Description*** | ***Goal values*** |
|---|---|---|
| P-factor | Expressed as a fraction (between 0-1) of the observed data that is within the 95PPU (model prediction uncertainty) bracket where 1 is equal to 100%. Considered as model error. | For flows: >0.7 |
| R-factor | Expressed as a ratio of the mean width of the 95PPU bracket and the standard deviation of the observed flows. | For flows: <1.5 (close to 1 is best) |

SUFI-2 works by running multiple iterations (less than five should be sufficient) of ≥300 simulations. An iteration is where parameter value ranges (minimum and maximum) are set in conjunction with determining the objective function, number of simulations, and variables being calibrated (flow). The number of simulations determine the parameter values (within the set range) applied using the Latin hypercube method (Abbaspour, 2015). Each parameter range requires an 'operator' to be selected. The operator was applied to the parameter range values determined by the

Latin hypercube sample method (and depended on number of simulations). The operators are defined as:

- Multiply: existing parameter value is multiplied (1+value)
- Replace: existing parameter value is replaced
- Add: value is added to the existing parameter value

For each parameter value applied a simulation is processed and the modelled flows are compared to observed flows. A ‘best simulation’ is identified in each iteration and new parameter ranges suggested for the subsequent iteration (if required). The parameter range(s) are the solution rather than the single parameter values applied for the ‘best simulation’ due to equifinality influence. The entire iterative procedure including processes and outputs for each iteration are depicted below in Figure 7A.

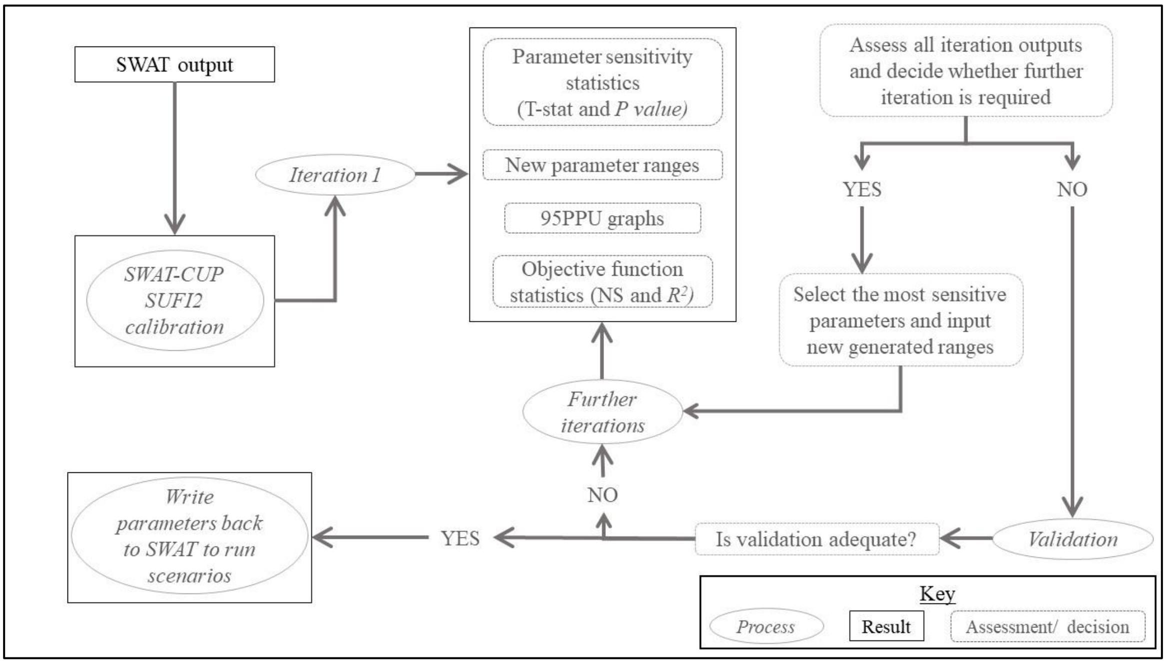



Figure 7A - SWAT-CUP calibration process framework.

With each iteration the 95PPU naturally narrows and with this, the P-factor and R-factor will decrease as the model aims to achieve a simulation that offers the best objective function statistic. For the Tarland model, the Nash-Sutcliffe efficiency (NS) (Nash and Sutcliffe, 1970) objective function was used based on its existing widespread use in assessing performance of hydrological models (Shaw *et al.* 2011). As shown in Equation 4.4, NS is a goodness-of-fit measure assessing the variance in error (residuals) from a range of -infinity to 1 where 1 is a perfect fit and 0 is as good as using the average of the observations (Beven, 2012; Shaw et al., 2011).

$$NS = 1 - \frac{\Sigma\,(Q_{obs} - Q_{sim})^2}{\Sigma\,(Q_{obs} - {Q_{obs}}^{x})^2} = 1 - \frac{\sigma_e^2}{\sigma_o^2}$$

Equation 4.4

Nash-Sutcliffe model efficiency measure (Nash and Sutcliffe, 1970)

Where: $Q_{obs}$ is observed discharge and $Q_{sim}$ is simulated discharge; ${Q_{obs}}^{x}$ is the mean observed discharge, and summation for all time-steps; $\sigma_e^2$ is the model residuals variance; and $\sigma_o^2$ is the variance of the observed discharge (Shaw *et al.*, 2011).

While not being used exclusively as an objective function in SWAT-CUP (for daily calibration), the coefficient of determination ($R^2$) was also considered alongside the NS statistic. The $R^2$ calculation is shown in Equation 4.5, where $_i$ is the $_i{}^{th}$ measured or simulated discharge. Calibration required a balance between achieving adequate 95PPU, P-factor, R-factor, NS (as objective function) and $R^2$; but also using a visual assessment of observed and simulated data for the best fit to peaks and peak timing.

$$R^2 = \frac{\left[\Sigma_i \left(Q_{obs,i} - {Q_{obs}}^{x}\right)\left(Q_{sim,i} - {Q_{sim}}^{x}\right)\right]^2}{\Sigma_i \left(Q_{obs,i} - {Q_{obs}}^{x}\right)^2 \Sigma_i \left(Q_{sim,i} - {Q_{sim}}^{x}\right)^2}$$

Equation 4.5

Coefficient of determination equation applied in SWAT-CUP

(Abbaspour, 2015)

**SWAT-CUP daily calibration and sensitivity analysis**

SWAT-CUP SUFI-2 was applied for daily calibration. Two iterations of 300 simulations were applied using minimum and maximum parameter ranges, and operators, suggested by Arnold et al. (2012b) and Abbaspour (2015), outlined in Table 4.6 (page 89). Objective function NS was assessed in conjunction with P-factor and R-factor statistics, as well as a visual assessment of the goodness-of-fit to observations. Visual assessment examined whether timing of simulated peaks coincided with observations and simulated peaks were of similar magnitude to observed peaks. The first iteration had a simulation which achieved these prerequisites best, for which the parameter ranges and fitted values are defined in Table 4.6 (pager 89); which also outline the final fitted operator and values applied. Following these parameter changes, the SCS runoff curve number for moisture condition (CN2.mgt) was edited. SWAT-CUP calculations had taken the value below the minimum threshold (35). The changes were in two stages:

- Stage 1 prior to calibration:
    - Urban based land uses had their CN2 number changed to 89
- Stage 2 after calibration:
    - Some CN2 values were <35 due to the multiplication applied to the values, these were then replaced by 38.

SWAT-CUP conducts a global sensitivity analysis during each iteration on parameters selected to be modified. The global method assesses sensitivity while all parameters are changing simultaneously, whereas a one-at-a-time (OAT) sensitivity does this for each parameter independently. SWAT-CUP users can use the *t*-stat and *P*-value (derived from the global sensitivity analysis) for each parameter to become more selective of parameters to use for iteration 2. The *t*-stat is the coefficient of a parameter divided by its standard error used to provide relative sensitivity based on linear estimates and the *P*-value tests whether the parameter has a significant change on model outputs (Abbaspour, 2015). Sensitive parameters are identified with larger *t*-stat values and lower *P*-value ($\leq$0.05) as shown in Table 4.6 (page 89). The general rule for selecting global sensitivity parameters to take forward was that the *P*-value was $\leq$0.05 and the *t*-stat was as high as possible: the *P*-value takes precedence (Abbaspour, 2015). Due to iteration 1 having the best simulation, the refined number of parameters were not required.

**SWAT-CUP Calibration and validation results**

The comparison between observed and simulated flows following calibration is shown in graphs A (Coull) and B (Aboyne) in Figure 7B. These also demonstrate the relevant statistics: P-factor, R-factor, NS and $R^2$, and are the best fit achievable using SWAT-CUP with additional manual adjustments on CN2.mgt. Coull has a better fit than Aboyne (Figure 7B), which is to be expected given there is greater uncertainty in Aboyne observed data (Figure 4.4, page 87). This demonstrated by the lack of fit of observed Aboyne flows to the GL-LMOM model in Figure 4.4. Uncertainty is addressed in more detail in Section 4.8.

As the model outputs are examined for changes to Ttp and Qpk (defined in Section 4.7), the calibration process required consideration of these factors. This was achieved by visually comparing simulated and observed flow graphs (Figure 7B) to assess whether Qpk and timing of peak were being represented by the SWAT. At Coull (graph A; Figure 7B), timing of peaks is good, but peaks were being underestimated and take longer to recede. Aboyne (graph B; Figure 7B) Qpk timing is consistently early until October 2005 but occur at the same time for larger peaks. The highest Aboyne peaks are underestimated with some receding limbs taking too long to recede (graph B; Figure 7B). Nevertheless, the goodness-of-fit and statistics for calibration was the best solution that could be achieved given the purpose of SWAT was to understand the relative change in Qpk.

Validation at Coull (graph C; Figure 7B) and Aboyne (graph D; Figure 7B) shows a similar outcome to the calibration. Peaks are underestimated at both sites and timing of peak is reasonably good despite the two events in March 2010 where Coull and Aboyne show the peak arriving and receding too soon (Figure 7B). The degree of uncertainty in the 95PPU shows peak flows are less uncertain for the validation period (Figure 7B). SWAT simulated flows were used to examine the *relative* change in Qpk rather than absolute change, thereby being more accommodating of some uncertainty. The calibrated and validated figures demonstrate there is a reasonable fit between simulated and observed flows which will enable analysis of riparian buffer strip scenarios and assess their impact on high flow events. This reasonable fit is supported by the P-factor, R-factor, NS and $R^2$ statistics, which are all within a suitable range to suggest at goodness-of-fit.

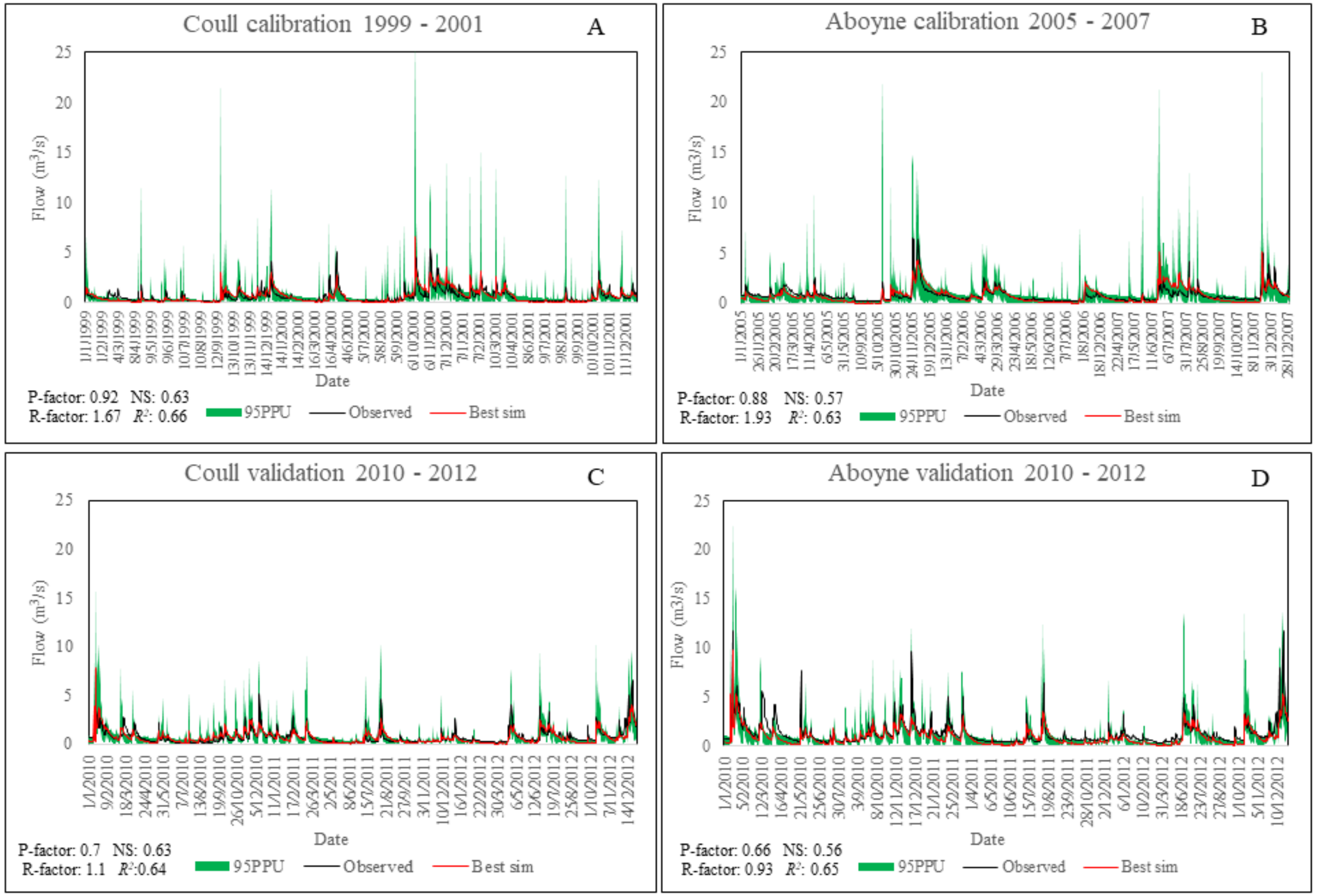



Figure 7B. Simulated and observed flows for calibration and validation of SWAT at Coull and Aboyne. Coull calibration (graph A) from 1999-2001; Aboyne calibration (graph B) from 2005-2007; Coull validation (graph C) from 2010-2012; and Aboyne validation (graph D) from 2010-2012. Statistics indicating goodness-of-fit are shown for Coull and Aboyne, for calibration and validation. Statistics are Nash-Sutcliffe Efficiency (NS), Pearson correlation ($R^2$), P-factor and R-factor

**Appendix 8**

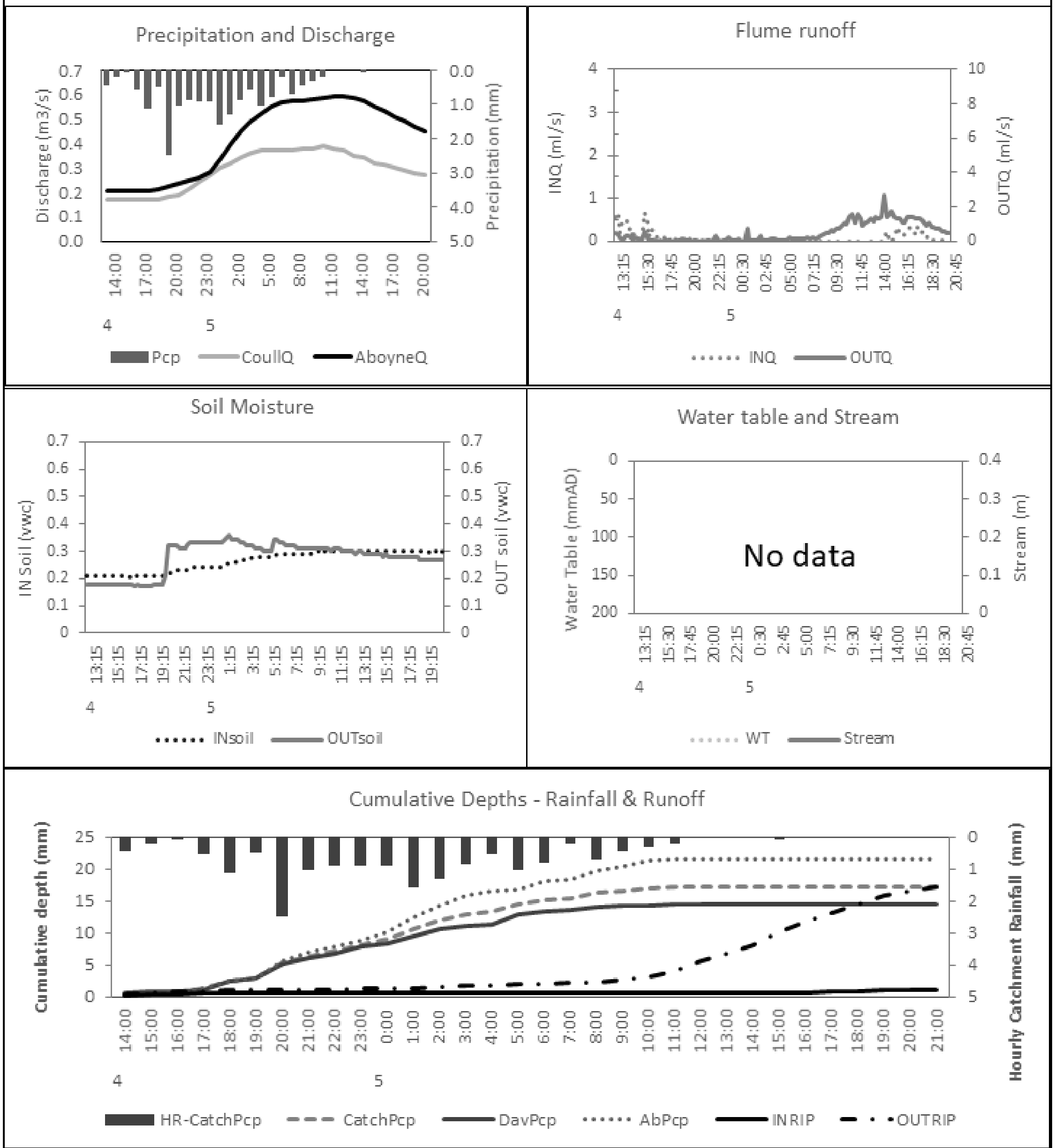
Manning's 'n' values (OV_N) used for hourly calibration.

| *Land use code* | *Description* | *OV_N value* |
|---|---|---|
| AGRL | Generic agricultural land | 0.09 |
| FRSD | Deciduous trees | 0.25 |
| FRSE | Coniferous trees | 0.25 |
| RNGB | Range – brush | 0.17 |
| RNGE | Range – grasses | 0.14 |
| TPAG | Acid grassland | 0.14 |
| TPHG | Heather grassland | 0.2 |
| TRLP | Rough low-productivity grassland | 0.11 |
| UIDU | Built-up urban | 0.01 |
| URML | Residential-Med/Low Density | 0.01 |
| WPAS | Winter pasture | 0.11 |
| BUF1 | Grassed buffer strips | 0.14 |
| BUF3 | Tree buffer strips | 0.25 |

**Appendix 9**

Rejected event example

## EVENT 107 – Start 4 June 2014 – Rejected event




| | | | | | |
|---|---|---|---|---|---|
| **Depth (mm)** | 17.2 | **INQ Area ($m^2$)** | 30 | **INRIP Q Ttp (hr)** | 1 |
| **Duration (hr)** | 32 | **OUTQ Area ($m^2$)** | 13.2 | **OUTRIP Q Ttp (hr)** | 25.5 |
| **Avg Intensity (mm/hr)** | 0.54 | **Coull Ttp (hr)** | 22 | **INRIP soil Ttp (hr)** | 25.25 |
| **Max Intensity (mm/hr)** | 2.48 | **Aboyne Ttp (hr)** | 23 | **OUTRIP soil Ttp (hr)** | 12.75 |
| **API30 (mm)** | 212.1 | **Land Use** | Upslope: all short crop (3)<br>Adjacent: short perimeter, bare soil centre (1) | | |

# Appendix 10

Runoff events

| Event | Event type | Date | Season | Land | | Precipitation | | | | API30 (mm) | Average Temp. (°C) | INRIP runoff | | | | OUTRIP runoff | | | | INRIP soil | | | OUTRIP soil | | | Stream | | W. Table | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Upslope | Adjacent | Depth (mm) | Duration (hr) | Intensity (mm/hr) | Max Intensity (mm) | | | Ttp (hr) | Qpk (ml/s) | Vol. (mm) | Contributing runoff area ($m^2$) | Ttp (hr) | Qpk (ml/s) | Vol. (mm) | Contributing runoff area ($m^2$) | Ttp (hr) | VWC Pk (%) | VWC change (%) | Ttp (hr) | VWC Pk (%) | VWC change (%) | Pk (m) | Ttp (hr) | Pk (mm) | Ttp (hr) |
| 2 | REJECT | 20-Dec-13 | Winter | 1 | 1 | 27.7 | 98 | 0.3 | 2.5 | 196 | 4.3 | 69.00 | 6.6 | 304 | | 68.75 | 0.1 | 2 | | 69.75 | 49% | 5% | | | | | | | |
| 4 | REJECT | 27-Dec-13 | Winter | 1 | 1 | 27.7 | 61 | 0.5 | 2.0 | 293 | 4.2 | 13.75 | 0.3 | 6 | | 21.75 | 0.0 | 0 | | 3.00 | 49% | 5% | | | | | | | |
| 8 | REJECT | 1-Jan-14 | Winter | 1 | 1 | 47.2 | 133 | 0.4 | 1.4 | 409 | 5.0 | 6.00 | 0.0 | 0 | | 6.00 | 0.0 | 0 | | 3.75 | 48% | 4% | | | | | | | |
| 27 | RUNOFF | 27-Jan-14 | Winter | 1 | 1 | 20.0 | 86 | 0.2 | 3.0 | 694 | 2.3 | 31.50 | 0.0 | 0 | 0 | 31.50 | 1632.4 | 90070 | 3600 | 58.00 | 47% | 2% | 58.00 | 56% | 19% | | | | |
| 31 | RUNOFF | 4-Feb-14 | Winter | 1 | 1 | 30.7 | 57 | 0.5 | 2.9 | 801 | 3.8 | 3.50 | 0.0 | 0 | 0 | 3.25 | 2008.2 | 600542 | 13200 | 26.50 | 48% | 4% | 16.75 | 50% | 13% | | | | |
| 35 | RUNOFF | 12-Feb-14 | Winter | 1 | 1 | 17.8 | 24 | 0.7 | 3.2 | 1013 | 3.1 | 7.75 | 5.4 | 226 | 9 | 7.75 | 12.8 | 585 | 22 | 9.75 | 51% | 4% | 7.50 | 42% | 13% | | | | |
| 36 | INFILT. | 14-Feb-14 | Winter | 1 | 1 | 21.9 | 39 | 0.6 | 3.3 | 1062 | 2.4 | 4.75 | 0.0 | 0 | 0 | 6.75 | 0.0 | 0 | 0 | 18.50 | 51% | 1% | 19.25 | 45% | 15% | | | | |
| 107 | REJECT | 4-Jun-14 | Summer | 3 | 1 | 17.2 | 32 | 0.5 | 2.5 | 212 | 12.1 | 4.25 | 0.7 | 154 | 6 | 4.00 | 2.6 | 1149 | 45 | 25.25 | 30% | 30% | 12.75 | 36% | 19% | | | | |
| 133 | REJECT | 26-Jul-14 | Summer | 4 | 3 | 18.1 | 30 | 0.6 | 5.0 | 195 | 15.7 | 6.75 | | | | 6.75 | | | | | | | | | | | | | |
| 137 | REJECT | 2-Aug-14 | Summer | 4 | 3 | 18.7 | 22 | 0.9 | 5.7 | 252 | 14.6 | 7.25 | | | | 8.50 | | | | | | | | | | | | | |
| 140 | REJECT | 8-Aug-14 | Summer | 4 | 3 | 29.6 | 20 | 1.5 | 15.5 | 346 | 12.8 | 48.75 | | | | 4.25 | | | | | | | | | | | | | |
| 141 | REJECT | 10-Aug-14 | Summer | 4 | 3 | 38.5 | 29 | 1.3 | 6.5 | 410 | 12.7 | 5.75 | | | | 5.75 | | | | | | | | | | | | | |
| 172 | REJECT | 3-Oct-14 | Autumn | 5 | 4 | 16.4 | 29 | 0.6 | 2.8 | 200 | 7.2 | 30.00 | 0.2 | 11 | 1 | 21.50 | 2.7 | 240 | 10 | 8.25 | 8% | 8% | 16.00 | 39% | 38% | | | 17.7 | 14.25 |
| 174 | RUNOFF | 6-Oct-14 | Autumn | 5 | 4 | 67.2 | 62 | 1.1 | 6.2 | 208 | 8.6 | 36.00 | 3.6 | 724 | 7 | 37.25 | 163.4 | 8798 | 89 | 36.50 | 16% | 11% | 37.50 | 67% | 37% | | | 88.7 | 36.75 |
| 200 | RUNOFF | 13-Nov-14 | Autumn | 5 | 4 | 21.9 | 34 | 0.6 | 3.4 | 415 | 9.2 | 21.50 | 0.3 | 9 | 0 | 27.75 | 414.2 | 8804 | 270 | 25.50 | 28% | 28% | 26.50 | 69% | 33% | | | 74.7 | 25.00 |
| 201 | RUNOFF | 15-Nov-14 | Autumn | 5 | 4 | 42.2 | 97 | 0.4 | 2.3 | 448 | 7.7 | 83.00 | 1.5 | 72 | 1 | 34.00 | 145.5 | 4592 | 73 | 8.25 | 30% | 30% | 9.25 | 65% | 29% | | | 69.8 | 8.25 |
| 285 | INFILT. | 3-May-15 | Spring | 8 | 2 | 19.2 | 24 | 0.8 | 3.4 | 197 | 4.3 | 0.00 | 0.0 | 0 | 0 | 0.00 | 0.0 | 0 | 0 | 13.75 | 36% | 36% | 19.50 | 39% | 13% | 0.2 | 15.00 | 96.8 | 14.00 |
| 343 | REJECT | 16-Jul-15 | Summer | 9 | 5 | 19.9 | 24 | 0.8 | 5.2 | 419 | 12.8 | 18.75 | 0.7 | 72 | 3 | 14.00 | 1.3 | 744 | 25 | 11.75 | 44% | 6% | 12.75 | 40% | 11% | 0.2 | 16.00 | 53.1 | 13.00 |
| 362 | REJECT | 14-Aug-15 | Summer | 10 | 6 | 20.4 | 45 | 0.5 | 2.5 | 323 | 12.4 | 31.75 | 9.4 | 3100 | 100 | 31.75 | 29.6 | 4569 | 176 | 32.00 | 42% | 11% | 34.25 | 38% | 38% | 0.2 | 31.25 | 29.4 | 33.50 |
| 367 | RUNOFF | 24-Aug-15 | Summer | 10 | 6 | 32.1 | 29 | 1.1 | 6.7 | 313 | 13.9 | 16.00 | 40.2 | 6616 | 148 | 19.25 | 44.1 | 5487 | 113 | 4.00 | 45% | 7% | 19.50 | 45% | 9% | 0.3 | 19.25 | 87.0 | 4.00 |
| 386 | RUNOFF | 20-Sep-15 | Autumn | 11 | 7 | 23.9 | 47 | 0.5 | 5.2 | 311 | 11.0 | 12.50 | 0.0 | 0 | 0 | 19.00 | 28.7 | 3172 | 89 | 19.25 | 41% | 9% | 22.75 | 40% | 39% | 0.2 | 22.50 | 42.5 | 22.75 |
| 393 | RUNOFF | 5-Oct-15 | Autumn | 11 | 7 | 16.2 | 33 | 0.5 | 3.7 | 196 | 13.2 | 24.50 | 0.0 | 0 | 0 | 19.25 | 19.6 | 1881 | 78 | 20.00 | 40% | 10% | 20.25 | 39% | 13% | 0.2 | 19.50 | 39.5 | 20.25 |
| 442 | INFILT. | 4-Dec-15 | Winter | 11 | 7 | 19.1 | 47 | 0.4 | 1.8 | 282 | 7.5 | 31.00 | 2.6 | 366 | 13 | 31.75 | 0.2 | 3 | 0 | 31.50 | 44% | 5% | 32.25 | 70% | 32% | 0.3 | 32.25 | 77.5 | 33.00 |

## Appendix 11

Spatial distribution of Chl-a concentrations for each transect on each month of measurement at the buffered and non-buffered sites. Colour spectrum ranges from green (low), yellow (moderate) and red (high) to represent level of Chl-a concentrations. Light blue sections at the buffered site indicate transects where not data is available.

**Non-buffered site**

| Date | *Transect* | *Right Bank* | *Centre* | *Left Bank* | *Transect Average* | *Monthly Median* |
|---|---|---|---|---|---|---|
| 3-Apr-14 | 10 | 1.1 | 29.6 | 34.0 | 21.6 | 33.1 |
| | 9 | 38.6 | 31.5 | 31.9 | 34.0 | |
| | 8 | 35.4 | 33.1 | 34.9 | 34.5 | |
| | 7 | 29.5 | 39.1 | 38.4 | 35.7 | |
| | 6 | 26.2 | 16.3 | 33.9 | 25.5 | |
| | 5 | 37.9 | 0.0 | 33.9 | 23.9 | |
| | 4 | 30.4 | 2.2 | 0.3 | 11.0 | |
| | 3 | 31.6 | 35.5 | 38.1 | 35.1 | |
| | 2 | 82.0 | 35.4 | 34.9 | 50.8 | |
| | 1 | 34.0 | 4.6 | 1.3 | 13.3 | |
| | 0 | 0.0 | 39.8 | 0.0 | 13.3 | |
| 6-May-14 | 10 | 24.3 | 34.4 | 37.1 | 31.9 | 25.7 |
| | 9 | 21.6 | 20.8 | 26.8 | 23.1 | |
| | 8 | 25.5 | 21.5 | 40.9 | 29.3 | |
| | 7 | 25.1 | 41.2 | 42.6 | 36.3 | |
| | 6 | 25.7 | 16.9 | 113.8 | 52.1 | |
| | 5 | 41.4 | 0.6 | 34.8 | 25.6 | |
| | 4 | 34.6 | 37.5 | 34.2 | 35.4 | |
| | 3 | 25.2 | 17.6 | 35.8 | 26.2 | |
| | 2 | 28.8 | 2.6 | 0.0 | 10.5 | |
| | 1 | 24.3 | 23.2 | 51.4 | 33.0 | |
| | 0 | 20.6 | 0.0 | 44.0 | 21.5 | |
| 21-Aug-14 | 10 | 9.5 | 10.7 | 16.3 | 12.2 | 9.7 |
| | 9 | 10.0 | 6.9 | 30.0 | 15.6 | |
| | 8 | 19.3 | 7.8 | 8.3 | 11.8 | |
| | 7 | 16.7 | 8.2 | 8.7 | 11.2 | |
| | 6 | 9.1 | 8.9 | 8.2 | 8.7 | |
| | 5 | 350.2 | 7.9 | 15.7 | 124.6 | |
| | 4 | 14.3 | 3.1 | 10.1 | 9.2 | |
| | 3 | 36.3 | 6.8 | 0.0 | 14.4 | |
| | 2 | 20.3 | 8.3 | 9.5 | 12.7 | |
| | 1 | 14.7 | 9.7 | 11.9 | 12.1 | |
| | 0 | 10.1 | 9.9 | 5.5 | 8.5 | |
| 18-Sep-14 | 10 | 62.3 | 1.0 | 106.0 | 56.4 | 34.6 |
| | 9 | 2.0 | 5.8 | 29.2 | 12.3 | |
| | 8 | 246.8 | 5.0 | 39.0 | 96.9 | |
| | 7 | 32.6 | 0.6 | 1.1 | 11.4 | |
| | 6 | 0.0 | 0.0 | 37.7 | 12.6 | |
| | 5 | 336.9 | 34.6 | 72.5 | 148.0 | |
| | 4 | 2.6 | 1.0 | 1.7 | 1.8 | |
| | 3 | 136.6 | 221.6 | 100.0 | 152.7 | |
| | 2 | 56.9 | 58.2 | 54.2 | 56.4 | |
| | 1 | 3.4 | 4.5 | 36.5 | 14.8 | |
| | 0 | 0.0 | 55.7 | 91.7 | 49.1 | |
| 14-Oct-14 | 10 | 29.9 | 27.4 | 28.7 | 28.7 | 23.4 |
| | 9 | 16.7 | 27.1 | 19.4 | 21.1 | |
| | 8 | 27.1 | 23.4 | 0.0 | 16.8 | |
| | 7 | 0.3 | 0.1 | 10.1 | 3.5 | |
| | 6 | 32.9 | 33.5 | 26.1 | 30.8 | |
| | 5 | 6.7 | 26.6 | 0.6 | 11.3 | |
| | 4 | 0.6 | 0.0 | 42.4 | 14.3 | |
| | 3 | 46.4 | 4.0 | 17.6 | 22.7 | |
| | 2 | 26.9 | 28.7 | 4.7 | 20.1 | |
| | 1 | 1.9 | 1.2 | 1.3 | 1.5 | |
| | 0 | 56.7 | 103.0 | 47.1 | 68.9 | |
| 13-Nov-14 | 10 | 4.4 | 3.0 | 4.1 | 3.8 | 4.5 |
| | 9 | 25.6 | 4.7 | 46.6 | 25.6 | |
| | 8 | 3.1 | 26.6 | 2.8 | 10.8 | |
| | 7 | 4.5 | 3.0 | 10.8 | 6.1 | |
| | 6 | 7.2 | 2.7 | 0.0 | 3.3 | |
| | 5 | 3.2 | 2.8 | 7.3 | 4.4 | |
| | 4 | 8.8 | 3.1 | 2.9 | 4.9 | |
| | 3 | 327.9 | 3.3 | 3.6 | 111.6 | |
| | 2 | 0.0 | 19.7 | 25.6 | 15.1 | |
| | 1 | 3.8 | 25.0 | 5.4 | 11.4 | |
| | 0 | 35.1 | 9.5 | 27.5 | 24.0 | |
| 24-Feb-15 | 10 | 18.7 | 13.3 | 19.1 | 17.0 | 10.0 |
| | 9 | 15.8 | 16.3 | 47.3 | 26.5 | |
| | 8 | 12.1 | 16.4 | 0.5 | 9.7 | |
| | 7 | 0.0 | 17.1 | 16.7 | 11.3 | |
| | 6 | 0.0 | 0.0 | 0.3 | 0.1 | |
| | 5 | 0.0 | 3.8 | 10.0 | 4.6 | |
| | 4 | 1.2 | 0.0 | 22.6 | 7.9 | |
| | 3 | 16.6 | 3.0 | 10.9 | 10.2 | |
| | 2 | 39.8 | 19.3 | 23.8 | 27.6 | |
| | 1 | 9.8 | 9.1 | 9.9 | 9.6 | |
| | 0 | 0.0 | 0.0 | 0.0 | 0.0 | |
| 25-Mar-15 | 10 | 35.5 | 27.9 | 34.4 | 32.6 | 14.5 |
| | 9 | 0.0 | 11.8 | 36.3 | 16.0 | |
| | 8 | 3.0 | 1.3 | 33.9 | 12.7 | |
| | 7 | 32.5 | 0.0 | 41.6 | 24.7 | |
| | 6 | 0.2 | 20.6 | 37.2 | 19.3 | |
| | 5 | 40.1 | 0.0 | 24.7 | 21.6 | |
| | 4 | 20.6 | 0.1 | 5.7 | 8.8 | |
| | 3 | 15.4 | 17.4 | 4.5 | 12.4 | |
| | 2 | 27.9 | 11.5 | 7.8 | 15.7 | |
| | 1 | 4.0 | 0.0 | 0.3 | 1.4 | |
| | 0 | 21.8 | 13.9 | 14.5 | 16.7 | |
| 29-May-15 | 10 | 10.9 | 33.9 | 42.9 | 29.2 | 33.8 |
| | 9 | 48.2 | 30.3 | 55.5 | 44.7 | |
| | 8 | 54.2 | 67.5 | 42.3 | 54.7 | |
| | 7 | 24.2 | 92.4 | 0.6 | 39.1 | |
| | 6 | 24.3 | 4.0 | 1.5 | 9.9 | |
| | 5 | 8.0 | 8.4 | 0.0 | 5.5 | |
| | 4 | 33.8 | 0.4 | 0.0 | 11.4 | |
| | 3 | 45.1 | 163.2 | 282.7 | 163.7 | |
| | 2 | 78.0 | 236.8 | 44.6 | 119.8 | |
| | 1 | 50.0 | 41.4 | 15.5 | 35.6 | |
| | 0 | 32.2 | 0.0 | 0.1 | 10.8 | |

**Riparian buffer strip site**

| Date | *Transect* | *Right Bank* | *Centre* | *Left Bank* | *Transect Average* | *Monthly Median* |
|---|---|---|---|---|---|---|
| 3-Apr-14 | 10 | 40.2 | 36.9 | 40.2 | 39.1 | 36.9 |
| | 9 | 41.5 | 42.0 | 39.8 | 41.1 | |
| | 8 | 0.3 | 24.6 | 36.2 | 20.4 | |
| | 7 | 39.5 | 39.1 | 43.7 | 40.8 | |
| | 6 | 43.3 | 36.0 | 42.5 | 40.6 | |
| | 5 | 36.7 | 39.3 | 19.0 | 31.7 | |
| | 4 | 37.0 | 36.8 | 40.6 | 38.1 | |
| | 3 | 35.8 | 37.9 | 39.9 | 37.9 | |
| | 2 | 18.6 | 36.8 | 15.8 | 23.7 | |
| | 1 | 27.8 | 0.0 | 41.1 | 23.0 | |
| | 0 | 3.3 | 2.1 | 20.6 | 8.7 | |
| 6-May-14 | 10 | 1.4 | 15.9 | 38.9 | 18.7 | 27.9 |
| | 9 | 41.6 | 31.4 | 32.9 | 35.3 | |
| | 8 | 29.0 | 17.9 | 32.6 | 26.5 | |
| | 7 | 434.9 | 26.7 | 31.9 | 164.5 | |
| | 6 | 29.9 | 0.4 | 40.8 | 23.7 | |
| | 5 | 27.0 | 28.1 | 0.2 | 18.4 | |
| | 4 | 0.0 | 17.1 | 3.5 | 6.9 | |
| | 3 | 0.0 | 0.0 | 0.0 | 0.0 | |
| | 2 | 40.7 | 17.5 | 36.7 | 31.6 | |
| | 1 | 0.5 | 2.7 | 51.8 | 18.3 | |
| | 0 | 28.2 | 27.9 | 33.2 | 29.8 | |
| 21-Aug-14 | 10 | | | | | 3.4 |
| | 9 | | | | | |
| | 8 | 2.2 | 11.9 | 1.6 | 5.2 | |
| | 7 | | | | | |
| | 6 | 104.7 | 6.2 | 11.9 | 40.9 | |
| | 5 | 3.4 | 4.5 | 25.9 | 11.3 | |
| | 4 | 1.2 | 1.7 | 1.6 | 1.5 | |
| | 3 | | | | | |
| | 2 | 0.2 | 0.0 | 33.5 | 11.2 | |
| | 1 | 4.7 | 2.1 | 14.2 | 7.0 | |
| | 0 | 1.9 | 2.4 | 163.0 | 55.8 | |
| 18-Sep-14 | 10 | 35.3 | 21.2 | 28.9 | 28.5 | 28.0 |
| | 9 | 2.4 | 0.9 | 1.5 | 1.6 | |
| | 8 | 1.2 | 46.3 | 0.0 | 15.8 | |
| | 7 | 41.6 | 36.1 | 41.7 | 39.8 | |
| | 6 | 38.2 | 41.8 | 51.5 | 43.8 | |
| | 5 | 36.3 | 39.7 | 58.9 | 45.0 | |
| | 4 | 15.8 | 1.2 | 2.6 | 6.5 | |
| | 3 | 5.0 | 4.9 | 1.2 | 3.7 | |
| | 2 | 19.9 | 31.8 | 99.1 | 50.3 | |
| | 1 | 2.8 | 28.3 | 41.7 | 24.3 | |
| | 0 | 0.0 | 28.0 | 1.7 | 9.9 | |
| 14-Oct-14 | 10 | 57.1 | 0.9 | 21.4 | 26.5 | 1.1 |
| | 9 | 0.6 | 3.3 | 43.7 | 15.9 | |
| | 8 | 1.2 | 0.4 | 0.0 | 0.5 | |
| | 7 | 27.1 | 23.1 | 26.1 | 25.4 | |
| | 6 | 51.5 | 7.4 | 73.3 | 44.1 | |
| | 5 | 69.0 | 16.9 | 40.6 | 42.2 | |
| | 4 | 43.0 | 0.4 | 0.4 | 14.6 | |
| | 3 | 0.6 | 0.7 | 0.6 | 0.6 | |
| | 2 | 0.6 | 0.6 | 0.9 | 0.7 | |
| | 1 | 0.9 | 1.1 | 0.8 | 0.9 | |
| | 0 | 0.6 | 4.2 | 0.6 | 1.8 | |
| 13-Nov-14 | 10 | 29.7 | 23.9 | 1.3 | 18.3 | 1.7 |
| | 9 | 35.2 | 2.5 | 1.3 | 13.0 | |
| | 8 | 1.7 | 1.5 | 1.3 | 1.5 | |
| | 7 | 16.6 | 46.8 | 10.5 | 24.6 | |
| | 6 | 27.0 | 0.0 | 18.9 | 15.3 | |
| | 5 | 3.5 | 26.5 | 25.1 | 18.4 | |
| | 4 | 2.2 | 1.7 | 1.3 | 1.7 | |
| | 3 | 1.4 | 2.1 | 1.7 | 1.7 | |
| | 2 | 1.4 | 24.6 | 1.7 | 9.2 | |
| | 1 | 15.9 | 1.4 | 1.6 | 6.3 | |
| | 0 | 1.6 | 1.5 | 1.7 | 1.6 | |
| 24-Feb-15 | 10 | | | | | 12.4 |
| | 9 | | | | | |
| | 8 | | | | | |
| | 7 | | | | | |
| | 6 | 12.4 | 17.2 | 25.3 | 18.3 | |
| | 5 | 18.6 | 13.1 | 29.5 | 20.4 | |
| | 4 | 30.8 | 1.8 | 30.8 | 21.1 | |
| | 3 | 0.0 | 13.4 | 0.5 | 4.6 | |
| | 2 | 23.4 | 0.4 | 1.2 | 8.3 | |
| | 1 | 0.9 | 0.2 | 5.0 | 2.0 | |
| | 0 | 37.0 | 0.2 | 0.2 | 12.5 | |
| 25-Mar-15 | 10 | 0.0 | 11.7 | 4.3 | 5.3 | 4.7 |
| | 9 | 52.5 | 0.0 | 20.3 | 24.3 | |
| | 8 | 17.1 | 1.0 | 23.5 | 13.9 | |
| | 7 | 23.1 | 0.2 | 0.2 | 7.8 | |
| | 6 | 7.9 | 0.6 | 16.4 | 8.3 | |
| | 5 | 1.0 | 20.1 | 31.0 | 17.4 | |
| | 4 | 0.0 | 0.0 | 34.6 | 11.5 | |
| | 3 | 4.8 | 0.0 | 0.0 | 1.6 | |
| | 2 | 0.0 | 4.7 | 13.8 | 6.2 | |
| | 1 | 26.5 | 1.4 | 9.1 | 12.3 | |
| | 0 | 1.3 | 14.1 | 0.0 | 5.1 | |
| 29-May-15 | 10 | | | 47.4 | 47.4 | 18.3 |
| | 9 | 42.8 | 0.0 | 42.9 | 28.6 | |
| | 8 | 44.8 | 42.1 | 77.5 | 54.8 | |
| | 7 | 40.9 | 0.0 | 43.6 | 28.2 | |
| | 6 | 39.6 | 11.4 | 47.7 | 32.9 | |
| | 5 | 40.6 | 13.0 | 20.8 | 24.8 | |
| | 4 | 375.1 | 0.0 | 0.0 | 125.0 | |
| | 3 | 41.0 | 15.4 | 0.1 | 18.8 | |
| | 2 | 36.7 | 2.6 | 18.3 | 19.2 | |
| | 1 | 0.0 | 0.6 | 2.9 | 1.2 | |
| | 0 | 12.0 | 6.9 | 0.0 | 6.3 | |

**Appendix 12**

Percentage reduction in peak flow and volume tables. 10 m Buffer Scenario: percentage reduction in peak flow and volume for riparian buffer strips with grasses or trees at upper, middle and lower catchment scales.

| 10m Buffer | Upper catchment - Netherton | | | | | | Middle catchment - Coull | | | | | | Lower catchment - Aboyne | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Grass | | Trees | | Difference (Trees - Grass) | | Grass | | Trees | | Difference (Trees - Grass) | | Grass | | Trees | | Difference (Trees - Grass) | |
| Event Date | Qpk | Vol | Qpk | Vol. | Qpk | Vol | Qpk | Vol | Qpk | Vol. | Qpk | Vol | Qpk | Vol | Qpk | Vol. | Qpk | Vol |
| 23/04/00 | 17.1% | 10.0% | 17.1% | 10.1% | 0.00% | 0.11% | 11.6% | 7.7% | 11.9% | 9.1% | 0.3% | 1.4% | 9.2% | 7.7% | 9.4% | 7.9% | 0.1% | 0.2% |
| 21/10/02 | 12.6% | 6.3% | 12.6% | 6.4% | 0.00% | 0.15% | 11.0% | 5.5% | 11.7% | 5.7% | 0.6% | 0.2% | 8.2% | 5.5% | 8.2% | 5.6% | 0.0% | 0.1% |
| 20/11/02 | 6.4% | 4.3% | 6.4% | 4.4% | 0.00% | 0.14% | 4.8% | 3.5% | 4.8% | 3.4% | 0.0% | -0.1% | 3.6% | 3.5% | 4.1% | 3.7% | 0.5% | 0.2% |
| 22/11/02 | 6.8% | 5.0% | 6.8% | 5.2% | 0.00% | 0.12% | 4.7% | 3.9% | 5.0% | 4.6% | 0.3% | 0.7% | 3.9% | 3.9% | 4.7% | 4.1% | 0.8% | 0.2% |
| 21/10/09 | 2.1% | 2.6% | 2.1% | 2.7% | 0.00% | 0.10% | 6.5% | 7.9% | 6.8% | 6.2% | 0.4% | -1.8% | 9.1% | 7.9% | 9.3% | 8.2% | 0.1% | 0.2% |
| 01/11/09 | 4.9% | 4.9% | 4.9% | 5.1% | 0.00% | 0.13% | 3.1% | 3.5% | 3.6% | 4.1% | 0.5% | 0.6% | 4.3% | 3.5% | 4.3% | 3.6% | 0.0% | 0.1% |
| 15/01/10 | 9.9% | 10.3% | 10.3% | 11.0% | 0.43% | 0.65% | 4.6% | 9.2% | 4.8% | 5.9% | 0.2% | -3.3% | 7.0% | 9.2% | 6.8% | 9.1% | -0.2% | -0.1% |
| 10/08/11 | 11.5% | 7.4% | 11.5% | 7.6% | 0.00% | 0.16% | 6.9% | 4.7% | 7.3% | 5.9% | 0.5% | 1.3% | 5.6% | 4.7% | 5.8% | 4.8% | 0.2% | 0.1% |
| 21/06/12 | 12.4% | 9.1% | 12.4% | 9.4% | 0.00% | 0.22% | 10.2% | 8.4% | 10.7% | 9.3% | 0.5% | 0.8% | 9.9% | 8.4% | 10.3% | 8.8% | 0.4% | 0.3% |
| 11/10/12 | 12.1% | 11.3% | 12.1% | 11.4% | 0.00% | 0.11% | 13.6% | 12.7% | 14.0% | 12.8% | 0.4% | 0.1% | 17.3% | 12.7% | 17.4% | 12.9% | 0.2% | 0.2% |
| 14/12/12 | 10.2% | 7.3% | 10.2% | 7.5% | 0.00% | 0.21% | 5.2% | 4.5% | 6.3% | 4.4% | 1.1% | -0.1% | 6.6% | 4.5% | 6.8% | 4.7% | 0.2% | 0.2% |
| 20/12/12 | 9.2% | 5.2% | 9.2% | 5.3% | 0.00% | 0.09% | 6.8% | 4.4% | 7.1% | 4.8% | 0.2% | 0.4% | 5.6% | 4.4% | 6.5% | 4.5% | 0.9% | 0.1% |
| 18/01/14 | 15.7% | 8.2% | 15.7% | 8.4% | 0.00% | 0.17% | 7.2% | 5.5% | 7.6% | 6.5% | 0.3% | 1.0% | 7.1% | 5.5% | 8.0% | 5.6% | 0.9% | 0.1% |
| 27/01/14 | 8.3% | 6.0% | 8.3% | 6.1% | 0.00% | 0.09% | 6.8% | 5.3% | 7.2% | 5.7% | 0.4% | 0.4% | 6.4% | 5.3% | 6.5% | 5.4% | 0.1% | 0.1% |
| 05/02/14 | 5.7% | 2.7% | 5.7% | 2.8% | 0.00% | 0.09% | 2.3% | 3.4% | 2.4% | 2.8% | 0.1% | -0.6% | 3.8% | 3.4% | 3.8% | 3.2% | 0.0% | -0.1% |
| 10/08/14 | 4.5% | 3.8% | 4.5% | 3.9% | 0.00% | 0.13% | 8.7% | 8.8% | 9.0% | 7.0% | 0.3% | -1.8% | 10.0% | 8.8% | 10.3% | 9.0% | 0.2% | 0.2% |
| 07/10/14 | 8.3% | 8.5% | 8.3% | 8.6% | 0.00% | 0.08% | 7.6% | 7.2% | 8.1% | 8.0% | 0.5% | 0.8% | 6.6% | 7.2% | 6.7% | 7.3% | 0.1% | 0.0% |
| 14/11/14 | 8.8% | 6.9% | 8.8% | 7.1% | 0.00% | 0.18% | 7.8% | 6.3% | 8.3% | 6.6% | 0.6% | 0.3% | 7.9% | 6.3% | 8.2% | 6.5% | 0.3% | 0.2% |
| 26/12/15 | 8.4% | 8.4% | 8.7% | 8.6% | 0.36% | 0.17% | 4.9% | 5.8% | 5.5% | 6.4% | 0.6% | 0.7% | 5.6% | 5.8% | 5.7% | 6.0% | 0.1% | 0.2% |
| 20/12/15 | 7.5% | 7.5% | 7.5% | 7.7% | 0.00% | 0.21% | 6.6% | 6.5% | 7.1% | 6.6% | 0.5% | 0.0% | 8.4% | 6.5% | 8.8% | 6.7% | 0.4% | 0.2% |
| 02/01/16 | 9.4% | 7.2% | 9.4% | 7.3% | 0.00% | 0.14% | 4.3% | 6.0% | 4.7% | 6.4% | 0.4% | 0.4% | 5.7% | 6.0% | 5.7% | 6.2% | 0.0% | 0.1% |

20 m Buffer Scenario: percentage reduction in peak flow and volume for riparian buffer strips with grasses or trees at upper, middle and lower catchment scales.

| 20m Buffer | Upper catchment - Netherton | | | | | | Middle catchment - Coull | | | | | | Lower catchment - Aboyne | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Grass | | Trees | | Difference (Trees - Grass) | | Grass | | Trees | | Difference (Trees - Grass) | | Grass | | Trees | | Difference (Trees - Grass) | |
| Event Date | Qpk | Vol | Qpk | Vol. | Qpk | Vol | Qpk | Vol | Qpk | Vol. | Qpk | Vol | Qpk | Vol | Qpk | Vol. | Qpk | Vol |
| 23/04/00 | 16.7% | 10.1% | 16.7% | 10.0% | 0.00% | -0.15% | 11.9% | 9.1% | 11.9% | 9.1% | 0.0% | 0.0% | 9.4% | 8.0% | 9.4% | 7.9% | 0.0% | 0.0% |
| 21/10/02 | 12.5% | 6.4% | 12.5% | 6.3% | 0.00% | -0.15% | 11.7% | 5.7% | 11.7% | 5.7% | 0.0% | 0.0% | 8.2% | 5.6% | 8.2% | 5.6% | 0.0% | 0.0% |
| 20/11/02 | 6.2% | 4.4% | 6.2% | 4.3% | 0.00% | -0.13% | 4.8% | 3.4% | 4.8% | 3.4% | 0.0% | 0.0% | 4.1% | 3.7% | 4.1% | 3.7% | 0.0% | 0.0% |
| 22/11/02 | 6.6% | 5.2% | 6.6% | 5.0% | 0.00% | -0.14% | 5.0% | 4.6% | 5.0% | 4.6% | 0.0% | 0.0% | 4.7% | 4.1% | 4.7% | 4.1% | 0.0% | 0.0% |
| 21/10/09 | 2.1% | 2.7% | 2.1% | 2.7% | 0.00% | -0.03% | 6.8% | 6.1% | 6.8% | 6.2% | 0.0% | 0.1% | 9.4% | 8.2% | 9.4% | 8.2% | 0.0% | 0.0% |
| 01/11/09 | 4.6% | 5.1% | 4.6% | 5.0% | 0.00% | -0.10% | 3.6% | 4.1% | 3.6% | 4.1% | 0.0% | 0.0% | 4.3% | 3.6% | 4.3% | 3.6% | 0.0% | 0.1% |
| 15/01/10 | 9.2% | 10.9% | 9.4% | 10.4% | 0.21% | -0.52% | 4.7% | 5.9% | 4.7% | 5.9% | 0.0% | 0.0% | 6.8% | 9.0% | 6.6% | 8.9% | -0.2% | -0.1% |
| 10/08/11 | 11.2% | 7.6% | 11.2% | 7.4% | 0.00% | -0.16% | 7.3% | 5.9% | 7.3% | 5.9% | 0.0% | 0.0% | 5.8% | 4.8% | 5.8% | 4.8% | 0.0% | 0.0% |
| 21/06/12 | 12.1% | 9.4% | 12.1% | 9.1% | 0.00% | -0.22% | 10.6% | 9.2% | 10.6% | 9.3% | 0.0% | 0.0% | 10.3% | 8.8% | 10.3% | 8.8% | 0.0% | 0.0% |
| 11/10/12 | 11.7% | 11.4% | 11.7% | 11.3% | 0.00% | -0.09% | 14.1% | 12.7% | 14.1% | 12.8% | 0.0% | 0.0% | 17.7% | 13.1% | 17.9% | 12.9% | 0.2% | -0.2% |
| 14/12/12 | 9.9% | 7.4% | 9.9% | 7.3% | 0.00% | -0.15% | 6.6% | 4.4% | 6.6% | 4.4% | 0.0% | 0.0% | 7.2% | 5.1% | 7.2% | 5.1% | 0.0% | 0.0% |
| 20/12/12 | 8.8% | 5.3% | 8.8% | 5.2% | 0.00% | -0.09% | 7.1% | 4.7% | 7.1% | 4.8% | 0.0% | 0.0% | 6.5% | 4.5% | 6.5% | 4.5% | 0.0% | 0.0% |
| 18/01/14 | 15.7% | 8.4% | 15.7% | 8.2% | 0.00% | -0.15% | 7.6% | 6.5% | 7.6% | 6.5% | 0.0% | 0.0% | 8.0% | 5.6% | 8.0% | 5.6% | 0.0% | 0.0% |
| 27/01/14 | 8.3% | 6.1% | 8.3% | 6.0% | 0.00% | -0.09% | 7.1% | 5.7% | 7.1% | 5.7% | 0.0% | 0.0% | 6.5% | 5.3% | 6.5% | 5.3% | 0.0% | 0.0% |
| 05/02/14 | 5.7% | 2.8% | 5.7% | 2.7% | 0.00% | -0.08% | 2.4% | 2.8% | 2.4% | 2.8% | 0.0% | 0.0% | 3.8% | 3.2% | 3.8% | 3.2% | 0.0% | 0.0% |
| 10/08/14 | 4.5% | 3.9% | 4.5% | 3.8% | 0.00% | -0.07% | 9.0% | 7.0% | 9.0% | 7.0% | 0.0% | 0.1% | 10.3% | 9.0% | 10.3% | 9.0% | 0.0% | 0.0% |
| 07/10/14 | 8.0% | 8.6% | 8.0% | 8.5% | 0.00% | -0.08% | 8.1% | 8.0% | 8.1% | 8.0% | 0.0% | 0.0% | 6.7% | 7.3% | 6.7% | 7.4% | 0.0% | 0.0% |
| 14/11/14 | 8.5% | 7.1% | 8.5% | 6.9% | 0.00% | -0.14% | 8.3% | 6.6% | 8.3% | 6.6% | 0.0% | 0.0% | 8.2% | 6.5% | 8.2% | 6.5% | 0.0% | 0.0% |
| 26/12/15 | 8.4% | 8.6% | 8.4% | 8.4% | 0.00% | -0.17% | 5.5% | 6.4% | 5.5% | 6.4% | 0.0% | 0.0% | 5.8% | 6.0% | 5.8% | 6.0% | 0.0% | 0.0% |
| 20/12/15 | 7.2% | 7.7% | 7.2% | 7.5% | 0.00% | -0.20% | 7.1% | 6.5% | 7.1% | 6.6% | 0.0% | 0.0% | 8.8% | 6.7% | 8.8% | 6.7% | 0.0% | 0.0% |
| 02/01/16 | 9.3% | 7.3% | 9.3% | 7.2% | 0.00% | -0.14% | 4.3% | 6.4% | 4.3% | 6.4% | 0.0% | 0.0% | 5.7% | 6.1% | 5.7% | 6.1% | 0.0% | 0.0% |

30 m Buffer Scenario: percentage reduction in peak flow and volume for riparian buffer strips with grasses or trees at upper, middle and lower catchment scales.

| 30m Buffer | Upper catchment - Netherton | | | | | | Middle catchment - Coull | | | | | | Lower catchment - Aboyne | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Grass | | Trees | | Difference (Trees - Grass) | | Grass | | Trees | | Difference (Trees - Grass) | | Grass | | Trees | | Difference (Trees - Grass) | |
| Event Date | Qpk | Vol | Qpk | Vol. | Qpk | Vol | Qpk | Vol | Qpk | Vol. | Qpk | Vol | Qpk | Vol | Qpk | Vol. | Qpk | Vol |
| 23/04/00 | 17.1% | 10.1% | 17.1% | 10.1% | 0.00% | -0.02% | 12.0% | 9.2% | 12.0% | 9.1% | 0.0% | -0.1% | 9.4% | 7.9% | 9.4% | 7.9% | 0.0% | 0.0% |
| 21/10/02 | 12.3% | 6.5% | 12.3% | 6.5% | 0.00% | 0.00% | 12.3% | 5.8% | 12.3% | 5.8% | 0.0% | 0.0% | 8.2% | 5.7% | 8.2% | 5.7% | 0.0% | 0.0% |
| 20/11/02 | 6.2% | 4.4% | 6.2% | 4.4% | 0.00% | 0.01% | 4.8% | 3.4% | 4.8% | 3.4% | 0.0% | 0.0% | 4.1% | 3.7% | 4.1% | 3.7% | 0.0% | 0.0% |
| 22/11/02 | 6.8% | 5.2% | 6.8% | 5.2% | 0.00% | -0.02% | 5.1% | 4.6% | 5.1% | 4.6% | 0.0% | 0.0% | 4.7% | 4.1% | 4.7% | 4.2% | 0.0% | 0.0% |
| 21/10/09 | 2.6% | 2.9% | 2.6% | 3.0% | 0.00% | 0.06% | 7.0% | 6.2% | 7.2% | 6.3% | 0.2% | 0.1% | 9.5% | 8.3% | 9.7% | 8.4% | 0.1% | 0.1% |
| 01/11/09 | 4.1% | 4.9% | 5.2% | 5.2% | 1.03% | 0.35% | 3.7% | 4.1% | 3.9% | 4.2% | 0.2% | 0.1% | 5.2% | 3.8% | 5.2% | 4.0% | 0.0% | 0.2% |
| 15/01/10 | 9.4% | 10.5% | 9.9% | 10.6% | 0.43% | 0.04% | 5.2% | 6.3% | 5.1% | 6.2% | -0.1% | -0.1% | 8.2% | 10.4% | 7.8% | 10.2% | -0.4% | -0.2% |
| 10/08/11 | 11.5% | 7.6% | 11.5% | 7.6% | 0.00% | -0.02% | 7.7% | 6.0% | 7.7% | 6.0% | 0.0% | 0.0% | 5.9% | 4.9% | 6.0% | 4.9% | 0.1% | 0.0% |
| 21/06/12 | 12.4% | 9.5% | 12.4% | 9.4% | 0.00% | -0.06% | 10.6% | 8.7% | 10.7% | 9.3% | 0.1% | 0.6% | 10.3% | 8.8% | 10.4% | 8.9% | 0.1% | 0.1% |
| 11/10/12 | 12.7% | 11.7% | 12.7% | 11.7% | 0.00% | 0.00% | 14.5% | 13.0% | 14.5% | 13.0% | 0.0% | 0.0% | 18.2% | 13.1% | 18.2% | 13.1% | 0.0% | 0.0% |
| 14/12/12 | 10.5% | 7.7% | 10.5% | 7.8% | 0.00% | 0.03% | 7.1% | 4.7% | 7.1% | 4.7% | 0.0% | 0.0% | 7.0% | 4.9% | 7.0% | 4.9% | 0.0% | 0.0% |
| 20/12/12 | 9.2% | 5.3% | 9.2% | 5.3% | 0.00% | 0.00% | 7.1% | 4.7% | 7.1% | 4.8% | 0.0% | 0.0% | 6.5% | 4.5% | 6.5% | 4.5% | 0.0% | 0.0% |
| 18/01/14 | 15.3% | 8.4% | 15.3% | 8.4% | 0.00% | 0.01% | 7.7% | 6.6% | 7.8% | 6.6% | 0.1% | 0.0% | 8.0% | 5.8% | 8.0% | 5.8% | 0.0% | 0.0% |
| 27/01/14 | 8.3% | 6.1% | 8.3% | 6.1% | 0.00% | -0.01% | 7.2% | 5.7% | 7.2% | 5.7% | 0.0% | 0.0% | 6.6% | 5.4% | 6.6% | 5.4% | 0.0% | 0.0% |
| 05/02/14 | 5.7% | 2.9% | 5.7% | 2.9% | 0.00% | -0.01% | 2.5% | 2.8% | 2.5% | 2.8% | 0.0% | 0.0% | 3.8% | 3.2% | 3.8% | 3.2% | 0.0% | 0.0% |
| 10/08/14 | 4.5% | 3.8% | 4.5% | 3.8% | 0.00% | 0.01% | 9.0% | 6.9% | 9.3% | 7.0% | 0.3% | 0.1% | 10.0% | 8.9% | 10.3% | 9.0% | 0.2% | 0.0% |
| 07/10/14 | 8.5% | 8.8% | 8.5% | 8.8% | 0.00% | 0.01% | 8.4% | 8.2% | 8.5% | 8.2% | 0.1% | 0.0% | 7.4% | 9.2% | 7.5% | 9.2% | 0.1% | 0.0% |
| 14/11/14 | 8.8% | 7.2% | 8.8% | 7.2% | 0.00% | -0.01% | 8.6% | 6.7% | 8.6% | 6.7% | 0.0% | 0.0% | 8.5% | 6.7% | 8.5% | 6.7% | 0.0% | 0.0% |
| 26/12/15 | 8.7% | 8.6% | 8.7% | 8.6% | 0.00% | 0.00% | 5.8% | 6.6% | 5.8% | 6.6% | 0.0% | 0.0% | 6.1% | 6.2% | 6.1% | 6.3% | 0.0% | 0.0% |
| 20/12/15 | 7.7% | 7.8% | 7.7% | 7.8% | 0.00% | 0.03% | 7.1% | 6.7% | 7.1% | 6.7% | 0.0% | 0.0% | 8.8% | 6.8% | 8.8% | 6.8% | 0.0% | 0.0% |
| 02/01/16 | 9.2% | 7.3% | 9.2% | 7.3% | 0.00% | 0.00% | 4.7% | 6.4% | 4.7% | 6.4% | 0.0% | 0.0% | 5.7% | 6.2% | 5.7% | 6.2% | 0.0% | 0.0% |

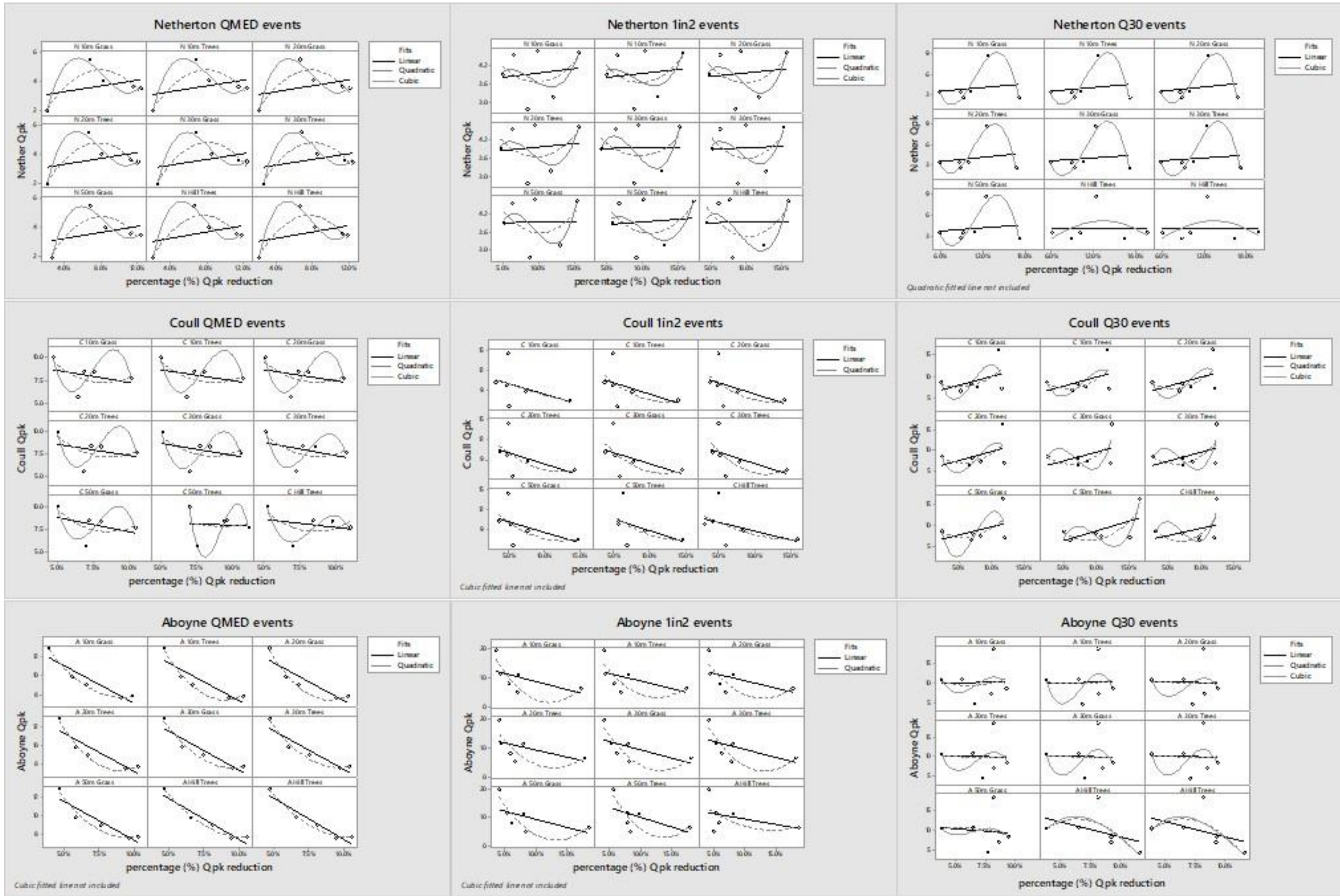
50 m Buffer Scenario: percentage reduction in peak flow and volume for riparian buffer strips with grasses or trees at upper, middle and lower catchment scales.

| 50m Buffer | Upper catchment - Netherton | | | | | | Middle catchment - Coull | | | | | | Lower catchment - Aboyne | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Grass | | Trees | | Difference (Trees - Grass) | | Grass | | Trees | | Difference (Trees - Grass) | | Grass | | Trees | | Difference (Trees - Grass) | |
| Event Date | Qpk | Vol | Qpk | Vol. | Qpk | Vol | Qpk | Vol | Qpk | Vol. | Qpk | Vol | Qpk | Vol | Qpk | Vol. | Qpk | Vol |
| 23/04/00 | 17.1% | 10.1% | 17.5% | 10.5% | 0.39% | 0.34% | 12.0% | 9.2% | 15.1% | 11.2% | 3.0% | 2.0% | 9.5% | 8.0% | 12.2% | 10.2% | 2.8% | 2.2% |
| 21/10/02 | 12.4% | 6.5% | 13.3% | 6.9% | 0.94% | 0.42% | 11.7% | 5.9% | 16.6% | 8.0% | 4.9% | 2.1% | 8.2% | 5.8% | 9.8% | 8.0% | 1.6% | 2.2% |
| 20/11/02 | 6.2% | 4.4% | 6.6% | 4.7% | 0.44% | 0.26% | 4.8% | 3.5% | 6.2% | 4.7% | 1.4% | 1.2% | 4.1% | 3.7% | 5.6% | 5.1% | 1.5% | 1.3% |
| 22/11/02 | 6.8% | 5.2% | 7.3% | 5.4% | 0.55% | 0.26% | 5.0% | 4.7% | 7.0% | 6.3% | 2.0% | 1.6% | 4.7% | 4.2% | 7.0% | 6.0% | 2.3% | 1.8% |
| 21/10/09 | 2.6% | 3.0% | 2.6% | 3.2% | 0.00% | 0.26% | 7.0% | 6.3% | 7.5% | 6.7% | 0.5% | 0.4% | 9.7% | 8.4% | 10.1% | 8.8% | 0.4% | 0.4% |
| 01/11/09 | 5.2% | 5.1% | 5.7% | 5.7% | 0.52% | 0.61% | 3.5% | 4.2% | 5.6% | 6.6% | 2.1% | 2.4% | 5.2% | 3.8% | 7.8% | 6.6% | 2.6% | 2.8% |
| 15/01/10 | 9.4% | 10.5% | 10.1% | 10.7% | 0.64% | 0.19% | 5.2% | 6.3% | 5.6% | 6.1% | 0.4% | -0.2% | 8.3% | 10.6% | 8.3% | 9.9% | 0.0% | -0.7% |
| 10/08/11 | 11.2% | 7.5% | 11.8% | 7.8% | 0.56% | 0.34% | 7.2% | 5.9% | 9.6% | 7.5% | 2.4% | 1.6% | 5.8% | 4.8% | 8.2% | 6.6% | 2.3% | 1.8% |
| 21/06/12 | 12.4% | 9.4% | 12.7% | 9.6% | 0.29% | 0.20% | 10.5% | 8.6% | 11.1% | 9.2% | 0.7% | 0.5% | 10.3% | 8.8% | 11.3% | 9.8% | 1.0% | 1.1% |
| 11/10/12 | 13.0% | 12.1% | 13.0% | 12.1% | 0.00% | 0.05% | 14.6% | 13.3% | 14.6% | 13.1% | 0.0% | -0.2% | 18.5% | 13.5% | 17.9% | 13.1% | -0.6% | -0.3% |
| 14/12/12 | 10.8% | 8.1% | 11.0% | 8.3% | 0.29% | 0.22% | 6.9% | 5.2% | 6.0% | 4.4% | -0.9% | -0.8% | 7.7% | 5.7% | 7.7% | 6.4% | 0.0% | 0.7% |
| 20/12/12 | 8.8% | 5.3% | 9.6% | 5.9% | 0.80% | 0.64% | 7.1% | 4.8% | 9.8% | 7.6% | 2.7% | 2.8% | 6.5% | 4.4% | 9.1% | 7.5% | 2.6% | 3.1% |
| 18/01/14 | 15.5% | 8.4% | 17.2% | 8.8% | 1.74% | 0.40% | 7.6% | 6.6% | 9.4% | 8.8% | 1.8% | 2.2% | 8.0% | 5.8% | 9.7% | 8.1% | 1.8% | 2.3% |
| 27/01/14 | 8.3% | 6.1% | 8.9% | 6.6% | 0.57% | 0.51% | 7.1% | 5.7% | 9.6% | 8.5% | 2.6% | 2.7% | 6.6% | 5.4% | 9.2% | 8.2% | 2.6% | 2.8% |
| 05/02/14 | 5.7% | 2.9% | 7.5% | 3.4% | 1.81% | 0.49% | 2.4% | 2.9% | 5.0% | 5.9% | 2.6% | 3.0% | 3.8% | 3.3% | 6.8% | 6.6% | 3.0% | 3.3% |
| 10/08/14 | 4.5% | 3.6% | 4.5% | 3.8% | 0.00% | 0.22% | 8.7% | 6.9% | 9.3% | 7.1% | 0.6% | 0.3% | 10.3% | 8.9% | 10.8% | 9.3% | 0.5% | 0.3% |
| 07/10/14 | 8.5% | 9.0% | 8.8% | 9.2% | 0.25% | 0.24% | 8.1% | 8.3% | 9.4% | 9.5% | 1.3% | 1.2% | 7.6% | 9.3% | 9.0% | 10.6% | 1.3% | 1.3% |
| 14/11/14 | 9.1% | 7.3% | 9.4% | 7.5% | 0.30% | 0.22% | 8.3% | 6.8% | 10.7% | 8.4% | 2.4% | 1.6% | 8.6% | 6.7% | 10.8% | 8.5% | 2.1% | 1.8% |
| 26/12/15 | 8.7% | 8.6% | 9.1% | 8.9% | 0.36% | 0.31% | 5.5% | 6.6% | 6.7% | 8.1% | 1.2% | 1.5% | 6.1% | 6.3% | 7.8% | 8.0% | 1.7% | 1.7% |
| 20/12/15 | 7.7% | 7.8% | 7.8% | 8.1% | 0.15% | 0.31% | 7.1% | 6.6% | 8.6% | 8.2% | 1.5% | 1.6% | 8.8% | 6.9% | 11.0% | 8.4% | 2.2% | 1.6% |
| 02/01/16 | 9.2% | 7.3% | 10.8% | 7.7% | 1.57% | 0.46% | 4.7% | 6.5% | 7.1% | 9.1% | 2.4% | 2.6% | 5.7% | 6.2% | 8.5% | 8.9% | 2.8% | 2.7% |

**Appendix 13**

The relationship between magnitude of Qpk and %↓Qpk at the three spatial scales for all buffer scenarios was explored. Fitted line plots (see Figure below) were applied to QMED, 1 in 2 and Q30 events (other return periods had n<3 and were excluded). The following differences in the relationship between Qpk and %↓Qpk at the upper, middle and lower catchment scales are evident:

- QMED events
  - Lower catchment had a negative relationship whereby lower Qpk would equate to a higher %↓Qpk (and vice versa).
  - The middle and upper catchment had a polynomial (cubic) relationship between Qpk and %↓Qpk. This essentially translates as there being instances where a similar value of Qpk could result in different percentages of reduction in Qpk (determined by where the polynomial line crossed a hypothetical X axis).
- 1 in 2 events
  - The lower and middle catchment Qpk relationship with %↓Qpk became similar at 1 in 2 year return period as both were quadratic with a similar shape of relationship.
  - In the lower catchment the quadratic relationship turning point was more pronounced whereby %↓Qpk increases as Qpk increases. This occurred at ~12% reduction and ~3 $m^3/s$.
  - The middle catchment fitted line plots did not fit as well as the lower catchment but indicate a decreasing Qpk corresponds to an increasing %↓Qpk.
  - The upper catchment fitted regression lines do not fit a good relationship between Qpk and %↓Qpk.
- Q30 events
  - These events changed the relationship between Qpk and %↓Qpk at the lower catchment where all three types of fitted line did not fit well. Furthermore, the 50 m tree-buffer and hillslope trees demonstrate a quadratic fit, albeit not satisfactorily.
  - The middle catchment however, showed a cubic relationship but had its best fit between Qpk and %↓Qpk for the 50 m tree-buffer and hillslope tree scenarios.
  - The upper catchment had cubic relationship fitted very well for all scenarios except the 50 m tree-buffer and hillslope trees where a straight line indicates there is no relationship between Qpk and reduction in Qpk.




Fitted linear, quadratic and cubic regression plots for QMED (n=5), 1 in 2 (n=6) and Q30 (n=6) events at upper (Netherton), middle (Coull) and lower (Aboyne) catchment scale. Fitted line plots examine percentage reduction in Qpk and Qpk at each spatial scale. Missing cubic or quadratic fitted lines were due to the inappropriateness of the line being fitted and skewing the view of another prominent type of fitted line. 1 in 5, Q10 and >1 in 10 were not included because n ≤2.

The relationships between Qpk and %↓Qpk provide insight into the dynamics of spatial scales of effectiveness and magnitude of event at which the buffer scenarios were most effective. At catchment scale (Aboyne) the QMED and 1 in 2 events illustrated the %↓Qpk increased as Qpk decreased, but this relationship was not evident for Q30 events. Compared to the middle and upper catchment, Aboyne had the best relationship fit, indicating more certainty at these lower magnitude events. The middle catchment demonstrated a negative relationship between Qpk and %↓Qpk, which became positive for larger Q30 events. Coull catchment had lower uncertainty for QMED but higher uncertainty at 1 in 2 and Q30 events. The upper catchment had a consistent cubic relationship for all magnitudes of event with less uncertainty for QMED and Q30. However, the 50 m tree-buffer and hillslope tree scenario changed this relationship and demonstrated uncertainty.

## Appendix 14

Correlation results between percentage reduction in peak flow and runoff peak; and percentage reduction in peak flow and runoff volume

| *Key: N = Netherton, C = Coull, A = Aboyne* | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Correlation: % peak flow (Qpk) reduction vs. event conditions | | | | | | Correlation % Volume reduction vs. event conditions | | | | | |
| | | API30 | Pcp depth (mm) | Intensity (pcp/hr) | Duration (hr) | | | API30 | Pcp depth (mm) | Intensity (pcp/hr) | Duration (hr) |
| N-10m-Grass | $R^2$ | -0.14 | 0.07 | -0.28 | 0.32 | N-10m-Grass | $R^2$ | -0.51 | 0.02 | 0.08 | 0.03 |
| | *p-value* | 0.553 | 0.772 | 0.215 | 0.163 | | *p-value* | 0.017 | 0.931 | 0.717 | 0.896 |
| N-10m-Trees | $R^2$ | -0.15 | 0.06 | -0.28 | 0.31 | N-10m-Trees | $R^2$ | -0.52 | 0.02 | 0.09 | 0.02 |
| | *p-value* | 0.519 | 0.785 | 0.223 | 0.173 | | *p-value* | 0.016 | 0.946 | 0.691 | 0.935 |
| N-20m-Grass | $R^2$ | -0.13 | 0.08 | -0.28 | 0.32 | N-20m-Grass | $R^2$ | -0.51 | 0.02 | 0.09 | 0.02 |
| | *p-value* | 0.585 | 0.745 | 0.215 | 0.157 | | *p-value* | 0.017 | 0.940 | 0.696 | 0.925 |
| N-20m-Trees | $R^2$ | -0.13 | 0.08 | -0.28 | 0.32 | N-20m-Trees | $R^2$ | -0.52 | 0.02 | 0.09 | 0.03 |
| | *p-value* | 0.577 | 0.748 | 0.217 | 0.160 | | *p-value* | 0.017 | 0.934 | 0.708 | 0.905 |
| N-30m-Grass | $R^2$ | -0.19 | 0.06 | -0.26 | 0.30 | N-30m-Grass | $R^2$ | -0.53 | 0.02 | 0.10 | 0.01 |
| | *p-value* | 0.420 | 0.806 | 0.247 | 0.185 | | *p-value* | 0.013 | 0.948 | 0.653 | 0.960 |
| N-30m-Trees | $R^2$ | -0.18 | 0.05 | -0.27 | 0.30 | N-30m-Trees | $R^2$ | -0.53 | 0.01 | 0.11 | 0.01 |
| | *p-value* | 0.428 | 0.829 | 0.236 | 0.190 | | *p-value* | 0.013 | 0.955 | 0.644 | 0.974 |
| N-50m-Grass | $R^2$ | -0.18 | 0.05 | -0.26 | 0.28 | N-50m-Grass | $R^2$ | -0.53 | 0.01 | 0.11 | 0.00 |
| | *p-value* | 0.428 | 0.833 | 0.250 | 0.213 | | *p-value* | 0.013 | 0.960 | 0.648 | 0.985 |
| N-50m-Trees | $R^2$ | -0.10 | 0.10 | -0.29 | 0.33 | N-50m-Trees | $R^2$ | -0.52 | 0.02 | 0.08 | 0.04 |
| | *p-value* | 0.668 | 0.676 | 0.208 | 0.146 | | *p-value* | 0.016 | 0.922 | 0.725 | 0.876 |
| N-Hill-Trees | $R^2$ | -0.19 | 0.01 | -0.23 | 0.18 | N-Hill-Trees | $R^2$ | -0.53 | -0.04 | 0.08 | -0.06 |
| | *p-value* | 0.414 | 0.958 | 0.308 | 0.427 | | *p-value* | 0.014 | 0.854 | 0.743 | 0.789 |
| C-10m-Grass | $R^2$ | -0.42 | -0.05 | -0.08 | 0.12 | C-10m-Grass | $R^2$ | -0.68 | 0.04 | 0.30 | -0.09 |
| | *p-value* | 0.060 | 0.840 | 0.725 | 0.591 | | *p-value* | 0.001 | 0.869 | 0.186 | 0.707 |
| C-10m-Trees | $R^2$ | -0.45 | -0.05 | -0.07 | 0.11 | C-10m-Trees | $R^2$ | -0.59 | 0.06 | 0.17 | 0.02 |
| | *p-value* | 0.042 | 0.823 | 0.759 | 0.643 | | *p-value* | 0.005 | 0.812 | 0.458 | 0.922 |
| C-20m-Grass | $R^2$ | -0.45 | -0.08 | -0.08 | 0.08 | C-20m-Grass | $R^2$ | -0.59 | 0.06 | 0.17 | 0.03 |
| | *p-value* | 0.039 | 0.733 | 0.743 | 0.717 | | *p-value* | 0.005 | 0.810 | 0.468 | 0.911 |
| C-20m-Trees | $R^2$ | -0.45 | -0.08 | -0.08 | 0.08 | C-20m-Trees | $R^2$ | -0.59 | 0.06 | 0.17 | 0.02 |
| | *p-value* | 0.039 | 0.733 | 0.743 | 0.717 | | *p-value* | 0.005 | 0.812 | 0.458 | 0.922 |
| C-30m-Grass | $R^2$ | -0.47 | -0.06 | -0.07 | 0.09 | C-30m-Grass | $R^2$ | -0.61 | 0.05 | 0.18 | 0.02 |
| | *p-value* | 0.033 | 0.792 | 0.773 | 0.704 | | *p-value* | 0.003 | 0.823 | 0.447 | 0.938 |
| C-30m-Trees | $R^2$ | -0.47 | -0.06 | -0.06 | 0.08 | C-30m-Trees | $R^2$ | -0.61 | 0.05 | 0.19 | 0.01 |
| | *p-value* | 0.032 | 0.782 | 0.794 | 0.728 | | *p-value* | 0.003 | 0.833 | 0.421 | 0.975 |
| C-50m-Grass | $R^2$ | -0.47 | -0.05 | -0.06 | 0.10 | C-50m-Grass | $R^2$ | -0.62 | 0.05 | 0.18 | 0.01 |
| | *p-value* | 0.032 | 0.827 | 0.786 | 0.659 | | *p-value* | 0.003 | 0.828 | 0.447 | 0.957 |
| C-50m-Trees | $R^2$ | -0.24 | 0.03 | -0.25 | 0.30 | C-50m-Trees | $R^2$ | -0.36 | 0.16 | -0.05 | 0.28 |
| | *p-value* | 0.301 | 0.908 | 0.284 | 0.192 | | *p-value* | 0.105 | 0.487 | 0.836 | 0.215 |
| C-Hill-Trees | $R^2$ | -0.46 | -0.09 | -0.03 | 0.01 | C-Hill-Trees | $R^2$ | -0.60 | 0.02 | 0.18 | -0.05 |
| | *p-value* | 0.038 | 0.697 | 0.892 | 0.954 | | *p-value* | 0.004 | 0.932 | 0.430 | 0.841 |
| A-10m-Grass | $R^2$ | -0.60 | -0.03 | 0.18 | -0.07 | A-10m-Grass | $R^2$ | -0.68 | 0.04 | 0.30 | -0.09 |
| | *p-value* | 0.004 | 0.902 | 0.438 | 0.757 | | *p-value* | 0.001 | 0.869 | 0.186 | 0.707 |
| A-10m-Trees | $R^2$ | -0.58 | -0.06 | 0.15 | -0.08 | A-10m-Trees | $R^2$ | -0.69 | 0.04 | 0.30 | -0.09 |
| | *p-value* | 0.006 | 0.809 | 0.507 | 0.736 | | *p-value* | 0.001 | 0.866 | 0.180 | 0.703 |
| A-20m-Grass | $R^2$ | -0.59 | -0.06 | 0.16 | -0.09 | A-20m-Grass | $R^2$ | -0.70 | 0.04 | 0.31 | -0.09 |
| | *p-value* | 0.005 | 0.802 | 0.496 | 0.715 | | *p-value* | 0.000 | 0.877 | 0.177 | 0.686 |
| A-20m-Trees | $R^2$ | -0.58 | -0.06 | 0.16 | -0.08 | A-20m-Trees | $R^2$ | -0.70 | 0.04 | 0.31 | -0.09 |
| | *p-value* | 0.005 | 0.807 | 0.501 | 0.720 | | *p-value* | 0.000 | 0.869 | 0.170 | 0.687 |
| A-30m-Grass | $R^2$ | -0.62 | -0.07 | 0.17 | -0.11 | A-30m-Grass | $R^2$ | -0.72 | 0.02 | 0.34 | -0.13 |
| | *p-value* | 0.003 | 0.748 | 0.451 | 0.630 | | *p-value* | 0.000 | 0.940 | 0.128 | 0.565 |
| A-30m-Trees | $R^2$ | -0.62 | -0.07 | 0.18 | -0.11 | A-30m-Trees | $R^2$ | -0.72 | 0.02 | 0.35 | -0.14 |
| | *p-value* | 0.003 | 0.749 | 0.442 | 0.623 | | *p-value* | 0.000 | 0.943 | 0.123 | 0.552 |
| A-50m-Grass | $R^2$ | -0.63 | -0.08 | 0.18 | -0.12 | A-50m-Grass | $R^2$ | -0.73 | 0.01 | 0.34 | -0.14 |
| | *p-value* | 0.002 | 0.726 | 0.447 | 0.598 | | *p-value* | 0.000 | 0.959 | 0.127 | 0.540 |
| A-50m-Trees | $R^2$ | -0.52 | -0.04 | 0.03 | 0.03 | A-50m-Trees | $R^2$ | -0.66 | 0.11 | 0.19 | 0.08 |
| | *p-value* | 0.015 | 0.874 | 0.883 | 0.891 | | *p-value* | 0.001 | 0.636 | 0.412 | 0.728 |
| A-Hill-Trees | $R^2$ | -0.59 | -0.09 | 0.16 | -0.14 | A-Hill-Trees | $R^2$ | -0.77 | 0.03 | 0.39 | -0.15 |
| | *p-value* | 0.005 | 0.688 | 0.488 | 0.534 | | *p-value* | 0.000 | 0.884 | 0.077 | 0.512 |

## Appendix 15

Percentage of each soil type overlaid by each buffer scenario cumulatively at the upper (Netherton), middle (Coull), and lower catchment (Aboyne) scale. Coloured bars represent each scenario (10 m – green; 20 m – yellow, 30 m – blue; 50 m – red, and hillslope – aqua blue) and the proportion of the buffer area which overlaid each soil type.

| | *Scenario* | *Brown forest soil (BFS)* | *BFS with gleying* | *Humus-iron podzol* | *Iron podzol* | *Mineral alluvial soil* | *Noncalcareous gley* | *Peat* | *Peaty gley* | *Peaty podzol* | *Total area ($km^2$)* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Netherton (25.3km$^2$) | 10m | 14.91% | 0.42% | 7.17% | | 65.74% | 10.62% | | 0.73% | 0.41% | 0.5 |
| | 20m | 18.23% | 0.85% | 8.08% | | 60.97% | 10.72% | | 0.69% | 0.46% | 1.0 |
| | 30m | 23.23% | 1.68% | 9.57% | | 53.54% | 10.85% | | 0.62% | 0.52% | 1.5 |
| | 50m | 32.99% | 3.86% | 12.44% | | 38.92% | 10.62% | | 0.52% | 0.65% | 2.5 |
| | Hillslope | 28.02% | 0.91% | 30.51% | | 2.60% | 4.38% | | 0.00% | 33.57% | 3.7 |
| Coull (49.6km$^2$) | 10m | 9.3% | 1.5% | 9.1% | | 69.7% | 9.7% | | 0.4% | 0.3% | 1.0 |
| | 20m | 11.60% | 1.92% | 10.60% | | 65.05% | 9.97% | 0.00% | 0.35% | 0.51% | 2.0 |
| | 30m | 14.81% | 2.72% | 12.78% | | 58.48% | 10.19% | 0.01% | 0.31% | 0.69% | 3.0 |
| | 50m | 20.79% | 4.48% | 16.77% | | 46.42% | 10.25% | 0.03% | 0.26% | 1.00% | 5.0 |
| | Hillslope | 25.20% | 0.64% | 42.41% | | 2.80% | 3.00% | | 0.00% | 25.94% | 5.5 |
| Aboyne - whole catchment (67.8km$^2$) | 10m | 7.01% | 1.06% | 13.81% | | 67.17% | 9.13% | 1.18% | 0.40% | 0.23% | 1.4 |
| | 20m | 8.72% | 1.40% | 15.87% | | 62.77% | 9.37% | 1.13% | 0.37% | 0.37% | 2.8 |
| | 30m | 11.14% | 1.99% | 18.69% | | 56.71% | 9.52% | 1.11% | 0.33% | 0.51% | 4.1 |
| | 50m | 15.68% | 3.28% | 23.99% | 0.01% | 45.47% | 9.45% | 1.09% | 0.29% | 0.75% | 6.9 |
| | Hillslope | 19.56% | 0.50% | 51.45% | | 2.25% | 2.33% | | | 23.91% | 7.1 |
| HyGrp | | B | B | A | B | A | C | D | C | C | |
| HyGrp Infiltration status | | Moderate | Moderate | High | Moderate | High | Slow | Very slow | Slow | Slow | |

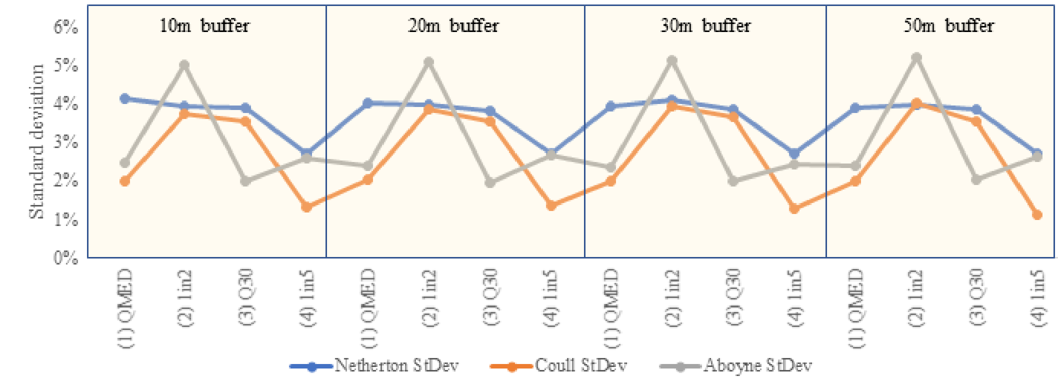
## Appendix 16

Percentage of each land use replaced by each buffer scenario cumulatively at the upper (Netherton), middle (Coull), and lower catchment (Aboyne) scale. Coloured bars represent each scenario (10 m – green; 20 m – yellow, 30 m – blue; 50 m – red, and hillslope – aqua blue) and the proportion of the buffer area which replaced each land use.

| | *Scenario* | *Acid grassland* | *Arable* | *Coniferous* | *Deciduous* | *Heather and dwarf shrub* | *Heather grass* | *Improved grassland* | *Rough low-productivity grassland* | *Suburban* | *Urban industrial* | *Total area ($km^2$)* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Netherton (25.3$km^2$) | 10m | 7.9% | 22.3% | 14.6% | 7.3% | 0.2% | 1.6% | 39.4% | 5.4% | 0.1% | 0.7% | 0.5 |
| | 20m | 7.3% | 23.0% | 14.5% | 7.1% | 0.3% | 1.6% | 40.3% | 5.5% | 0.1% | 0.5% | 1.0 |
| | 30m | 7.1% | 23.1% | 14.5% | 6.9% | 0.4% | 1.6% | 40.8% | 5.5% | 0.1% | 0.0% | 1.5 |
| | 50m | 7.4% | 23.3% | 14.1% | 6.2% | 0.5% | 1.6% | 41.2% | 5.3% | 0.1% | 0.3% | 2.5 |
| | Hillslope | 57.8% | 0.0% | 0.0% | 0.0% | 0.0% | 42.2% | 0.0% | 0.0% | 0.0% | 0.0% | 3.7 |
| Coull (49.6$km^2$) | 10m | 5.8% | 22.1% | 12.4% | 7.1% | 0.3% | 2.3% | 42.8% | 4.7% | 0.8% | 0.3% | 1.0 |
| | 20m | 5.5% | 22.0% | 12.4% | 7.0% | 0.3% | 2.3% | 43.1% | 4.7% | 0.8% | 0.3% | 2.0 |
| | 30m | 5.2% | 22.2% | 12.2% | 6.8% | 0.3% | 2.3% | 43.6% | 4.7% | 0.8% | 0.2% | 3.0 |
| | 50m | 5.3% | 22.5% | 12.3% | 6.3% | 0.4% | 2.2% | 44.2% | 4.7% | 0.8% | 0.2% | 5.0 |
| | Hillslope | 56.2% | 0.0% | 0.0% | 0.0% | 0.0% | 43.8% | 0.0% | 0.0% | 0.0% | 0.0% | 5.5 |
| Aboyne - whole catchment (67.8$km^2$) | 10m | 7.4% | 25.8% | 22.3% | 10.4% | 0.3% | 3.7% | 53.1% | 11.1% | 0.8% | 0.7% | 1.4 |
| | 20m | 6.9% | 26.2% | 22.7% | 10.2% | 0.4% | 3.9% | 53.8% | 11.1% | 0.8% | 0.6% | 2.8 |
| | 30m | 6.7% | 26.4% | 22.2% | 9.9% | 0.5% | 3.9% | 54.5% | 11.1% | 0.8% | 0.0% | 4.1 |
| | 50m | 6.9% | 26.9% | 22.4% | 9.1% | 0.6% | 3.9% | 55.7% | 10.9% | 0.7% | 0.3% | 6.9 |
| | Hillslope | 49.0% | 0.0% | 0.0% | 0.0% | 0.0% | 51.0% | 0.0% | 0.0% | 0.0% | 0.0% | 7.1 |

## Appendix 17

| | Scenario | Average % reduction Qpk QMED | 1in2 | Q30 | 1in5 | Q10 | >1in10 | Standard deviation QMED | 1in2 | Q30 | 1in5 | Q10 | >1in10 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Upper | N 10m Grass | 8.2% | 9.5% | **10.6%** | 6.4% | 7.5% | 9.4% | 4.1% | 3.9% | 3.9% | 2.7% | na | na |
| | N 10m Trees | 8.2% | 9.7% | **10.6%** | 6.4% | 7.5% | 9.4% | 4.1% | 3.9% | 3.9% | 2.7% | na | na |
| | N 20m Grass | 8.0% | 9.3% | **10.4%** | 6.4% | 7.2% | 9.3% | 4.0% | 4.0% | 3.8% | 2.7% | na | na |
| | N 20m Trees | 8.0% | 9.3% | **10.4%** | 6.4% | 7.2% | 9.3% | 4.0% | 4.0% | 3.8% | 2.7% | na | na |
| | N 30m Grass | 8.4% | 9.4% | **10.6%** | 6.4% | 7.7% | 9.2% | 4.0% | 4.1% | 3.9% | 2.7% | na | na |
| | N 30m Trees | 8.4% | 9.6% | **10.6%** | 6.4% | 7.7% | 9.2% | 4.0% | 3.8% | 3.9% | 2.7% | na | na |
| | N 50m Grass | 8.3% | 9.7% | **10.6%** | 6.4% | 7.7% | 9.2% | 3.9% | 4.0% | 3.9% | 2.7% | na | na |
| | N 50m Trees | 8.6% | 10.3% | **11.4%** | 6.7% | 7.8% | 10.8% | 4.0% | 4.3% | 3.6% | 3.1% | na | na |
| | N Hill Trees | 8.0% | 9.0% | **12.2%** | 5.9% | 7.5% | 9.4% | 4.0% | 4.3% | 5.1% | 3.0% | na | na |
| Middle | C 10m Grass | 7.2% | 6.4% | **7.4%** | 7.7% | 6.6% | 4.3% | 2.0% | 3.8% | 3.5% | 1.3% | na | na |
| | C 10m Trees | 7.6% | 6.7% | **7.9%** | 8.1% | 7.1% | 4.7% | 2.1% | 3.8% | 3.6% | 1.3% | na | na |
| | C 20m Grass | 7.6% | 6.7% | **8.0%** | 8.0% | 7.1% | 4.3% | 2.0% | 3.8% | 3.5% | 1.3% | na | na |
| | C 20m Trees | 7.6% | 6.7% | **8.0%** | 8.0% | 7.1% | 4.3% | 2.0% | 3.8% | 3.5% | 1.3% | na | na |
| | C 30m Grass | 7.8% | 6.9% | **8.3%** | 8.1% | 7.1% | 4.7% | 2.0% | 3.9% | 3.6% | 1.3% | na | na |
| | C 30m Trees | 7.8% | 7.0% | **8.3%** | 8.2% | 7.1% | 4.7% | 2.0% | 3.9% | 3.6% | 1.5% | na | na |
| | C 50m Grass | 7.5% | 6.9% | **8.1%** | 7.9% | 7.1% | 4.7% | 2.0% | 4.0% | 3.6% | 1.1% | na | na |
| | C 50m Trees | 8.9% | 8.0% | **10.5%** | 9.4% | 8.6% | 7.1% | 1.7% | 3.5% | 4.7% | 0.3% | na | na |
| | C Hill Trees | 8.3% | 7.0% | **8.9%** | 7.9% | 8.1% | 4.7% | 2.3% | 4.8% | 3.5% | 0.7% | na | na |
| Lower | A 10m Grass | 7.0% | 7.5% | 6.9% | 8.2% | **8.4%** | 5.7% | 2.5% | 5.0% | 2.0% | 2.6% | na | na |
| | A 10m Trees | 7.4% | 7.7% | 7.1% | 8.4% | **8.8%** | 5.7% | 2.3% | 5.0% | 1.9% | 2.7% | na | na |
| | A 20m Grass | 7.4% | 7.8% | 7.2% | 8.4% | **8.8%** | 5.7% | 2.4% | 5.1% | 1.9% | 2.7% | na | na |
| | A 20m Trees | 7.4% | 7.8% | 7.2% | 8.4% | **8.8%** | 5.7% | 2.4% | 5.2% | 1.9% | 2.7% | na | na |
| | A 30m Grass | 7.6% | 8.3% | 7.2% | 8.3% | **8.8%** | 5.7% | 2.4% | 5.1% | 2.0% | 2.4% | na | na |
| | A 30m Trees | 7.7% | 8.2% | 7.2% | 8.4% | **8.8%** | 5.7% | 2.4% | 5.1% | 2.0% | 2.6% | na | na |
| | A 50m Grass | 7.6% | 8.4% | 7.4% | 8.4% | **8.8%** | 5.7% | 2.4% | 5.2% | 2.0% | 2.6% | na | na |
| | A 50m Trees | 9.1% | 9.5% | 9.4% | 10.0% | **11.0%** | 8.5% | 1.7% | 4.3% | 2.0% | 1.1% | na | na |
| | A Hill Trees | 7.8% | 7.7% | 8.1% | 8.2% | **9.3%** | 5.7% | 2.3% | 5.5% | 2.7% | 2.3% | na | na |
| | sample n | 5 | 6 | 5 | 2 | 1 | 1 | 5 | 6 | 5 | 2 | 1 | 1 |




Average percentage (%) reduction in Qpk and standard deviation for each scenario at upper, middle and lower catchment scale for return periods (QMED, 1 in 2, Q30, 1 in 5, Q10 and >1 in 10). Grey text indicates irrelevant standard deviation due to sample number (n). Horizontal text is 50 m tree-based scenario, and vertical red text is the return period with highest % reduction in Qpk at each spatial scale. Line graph is a visual representation of standard deviation (uncertainty).

**Appendix 18**

Wildlife captured by field camera.